MENTAL PRACTICE: CLINICAL AND EXPERIMENTAL RESEARCH IN IMAGERY AND ACTION OBSERVATION

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MENTAL PRACTICE: CLINICAL AND EXPERIMENTAL RESEARCH IN IMAGERY AND ACTION OBSERVATION

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Photograph by John McPake

There is now strong evidence demonstrating that the brain simulates action and other functions. Such action simulation can be evoked through conscious mental rehearsal of movement or imagery, but also through passive action observation watching movements in others. Furthermore, there is evidence to suggest that mental rehearsal of movement, or mental practice, can produce improvements normally attributed to practising actual movements. It is currently assumed that such improvements are due to neural activation associated with action simulation. However the neuroscience of mental practice efficacy is still poorly understood. The aim of this research topic is to clarify the underlying mechanisms of mental practice, bringing evidence from cognitive neuroscience, experimental neuropsychology, sport and movement science, and clinical neurology. It also attempts to address confusion regarding the concepts of imagery and observation, which has hampered the progression of mental practice research both scientifically and applied. As well as reviews, theoretical, and position articles, this research topic includes original neuroimaging, experimental, and patient research addressing, among others, the following issues.

Neuroimaging studies provide strong evidence for action simulation, but the link to behavioural change and functional outcome is weak. What is the evidence that mental practice efficacy is driven by neuroplasticity processes evoked by action simulation? This research topic includes contributions on neural correlates and behaviour with regards to imagery and action observation.

Much of the mental practice efficacy evidence comes from longstanding research within sport science. However, what does mental practice entail in these contexts, and to what extent is it compatible with the cognitive neuroscience perspective of action simulation? This research topic will include contributions that consider both evidence and concepts with regards to imagery and action observation, in an attempt to build an interdisciplinary consensus on the nature and application of mental practice.

Mental practice is perceived as a promising motor rehabilitation technique, but critically there is lack of clarity or consensus on what mental practice treatment should entail. It is also not clear what are the most appropriate outcomes to measure imagery ability and cognitive or behavioural change following mental practice. A further important issue that needs consideration as part of this research topic is dosage, as it is currently unclear how much mental practice is appropriate and whether this depends on patient variables such as age, cognitive functioning, motor function, or pathophysiology.

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EDITORIAL
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Editorial: Mental practice: clinical and experimental research in imagery and action observation

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Keywords: mental practice, action simulation, action observation, imagery, cognitive neuroscience

This editorial accompanies 18 articles as part of a *Frontiers* research topic. The aim of this research topic was to clarify the underlying mechanisms involved in mental practice of action, bringing together evidence from a range of disciplines including cognitive neuroscience, experimental neuropsychology, sport and movement science, clinical neuropsychology and clinical neurology. The need to clarify the underlying mechanisms of mental practice is a pressing one. Mental practice of action has been explored in sport psychology for several decades, with the aim to use mental practice to improve sport performance. However, following the discovery of the mirror neuron system (see for example, Rizzolatti and Craighero, 2004), the perspective of mental practice has changed to a rationale based on neuroscience and to research focussed on understanding the neural processes of mental practice. Evidence that the brain simulates action has resulted in a common understanding of "functional equivalence" (Jeannerod, 1994): the idea that the *mental* representation of an action or percept in the person's mind is the neural "equivalent" to the *physical* action or *actual* percept. This ability to mentally represent action using the motor system allows for action simulation, providing conscious mental rehearsal of movement (imagery), but also allows for a common percept when observing the movements of others. Finally, in recent years, the disciplines of clinical neuropsychology and neurology have begun to use mental rehearsal of action, or *mental practice*, to produce improvements normally attributed to practicing actual movements.

At the heart of all of the research is the idea that mental practice of action uses equivalent neural processes to those used in action execution. Of course, there is debate on what one understands to be "equivalent," but the common reasoning seems to be that because mental practice (motor imagery and action observation) is functionally or neurally equivalent to actual practice, the efficacy principle of mental practice is that the motor areas are "trained," perhaps through Hebbian learning "firing-rewiring." Although the scientific foundation of this idea of action simulation is very sound in neuroimaging research (e.g., Sharma and Baron, 2013, this issue), the link to behavioral evidence or efficacy is currently weak. The neural correlates of mental practice are just that: correlates and do not justify inference about function, efficacy, or critical causality. There nevertheless seems to be reluctance in the field to address the underlying mechanisms of mental practice efficacy. This comes maybe as no surprise. A functional equivalence rationale for mental practice is intuitive and appealing and will therefore attract interest and funding. It is hardly in the researchers' interest to potentially undermine the idea by getting to the bottom of the matter.

We are now 15 or maybe 20 years into mental practice efficacy research based on the neural equivalence premise (Jackson et al., 2001). What is apparent is that the above simple interpretation of equivalence is not reflected in emerging data. It seems that mental practice efficacy is much more complex than simple Hebbian learning. There may be an analogy with the development of our understanding of the supplementary motor area (SMA) over that same time period. Initially SMA was thought of as a simple planning neural strip, but we have since understood the operation

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of SMA to be highly complex in the way it is involved in inhibition. For example, in studies using fMRI, motor imagery and action observation often do not activate the primary motor cortex (M1) because the SMA is thought to supresses the M1 activity (presumably preventing the individual from actually executing actions). The inherent role of inhibition in mental practice and the complexity of efficacy mechanisms still require further research. The popular notion that anything to do with the mirror neuron system is a simple matter of equivalence, or similarly that in applied contexts of mental practice equivalence is the end of the conversation, needs to change. We now need to go beyond what we are comfortable with and challenge what we know, even if we risk undermining the last decades of research.

There are still a lot of things that we do not know about the mechanisms of mental practice of action. What does each part of the brain engaged in mental practice actually do; how do processes relate to one another; what happens when different areas in the network are damaged? There are indications that insufficient drive to address the fundamentals of mental practice is starting to become a real issue of concern. The systematic review in this issue by Braun et al. (2013) concludes that the clinical evidence for mental practice efficacy in neuro-rehabilitation is weakening. The reasons for this seems to be the lack of theory-driven interventions, conceptual confusion (what does mental practice actually entail in practice?) and general methodological malaise including feasibility, dose, responders/non-responders, and adherence issues in larger scale trials that are more representative of clinical practice. Alternatively, when neuroscience evidence is carefully implemented in theory-driven clinical evaluation of mental practice, this may not translate to earlier reported clinical benefit (Ietswaart et al., 2011). Indeed, Malouin et al. (2013) in this issue highlight significant issues with the translation of experimental findings into clinical practice. Malouin et al.'s critical review is constructive, however, by suggesting ways in which the value of mental practice can be redeemed by addressing underlying mechanisms of mental practice efficacy. They conclude that the field must now truly put the use of mental practice to the test. Mental practice may indeed benefit the large number of stroke patients in neuro-rehabilitation, but unless mental practice is truly put to the test, this application may be superseded by other clinical innovations, for example, robotic assisted therapy. The field needs to deliver the necessary clarity on what exactly are the "active ingredients" of mental practice; what are the things that do not work and are mere distractions; which complexities play a role. Only then can we formulate effective guidance on what mental practice should actually entail in clinical practice. In the meantime, mental practice therapy in neuro-rehabilitation is already currently recommended treatment in many clinical guidelines. This current position means that we need to act fast in order to understand the processes and benefits of mental practice for clinical use. However, the current questionable guidance, range of possible uses, lack of efficacy etc. will likely undermine clinicians' willingness to adopt the treatment in the forthcoming years unless some clarity emerges.

Currently, much of the research effort goes to further documenting the correlates of mental practice, i.e., the fact that imagery and observation resonate with other motoric processes. In that respect, a number of the studies reported in this issue are exceptions to this rule in the way these studies ambitiously delineate the mental practice process by for example comparing the quasi-visual and the verbal-cognitive element of mental practice efficacy (Saimpont et al., 2013, this issue), or by contrasting the efficacy of different visual perspectives in mental practice (Callow et al., 2013, this issue; Yao et al., 2013, this issue), or by separating the impact of active imagery and passive observation (Eaves et al., 2014, this issue). It is an issue of concern, however, that such experimental approaches are generally not pursued (nor funded) as part of clinical evaluations, when now is the time to establish the finer details of mental practice efficacy in clinical contexts. We therefore advocate more high risk, high gain evaluations of mental practice that can establish the real impact of mental practice on the lives of real people in the clinic.

Further to bringing clarity with regards to the underlying mechanisms of mental practice, there is a real need to establish the modes of delivery and dosage. Clinicians furthermore need tools to make predictions of which patients will benefit and from what types of mental practice treatment. Lack of clarity on patient characteristics such as motor imagery ability can easily lead to miss-use of current findings exposing a risk of clinicians dismissing patients who they believe would not stand to benefit from mental practice–based rehabilitation. It would be great if we could say with some level of certainty whether a brain-damaged patient has an intact ability to use and benefit from mental practice therapies. Some authors would claim this can be done either through subjective methods such as vividness questionnaires, or through more objective methods such as mental chronometry (Milner, 1986), or monitoring automatic covert action simulation such as the cognitive hand mental rotation task established by Parsons (1987), or the response of the autonomic nervous system in mental practice as proposed by Collet et al. (2013, this issue). There is pressure on the research community to provide reliable measures of motor imagery ability on which clinicians can base a decision whether to provide a patient with mental practice rehabilitation. But quite possibly we do not (yet) have reliable tools on which such important decisions can be based. A study by de Vries et al. (2013, this issue) documenting motor imagery ability in stroke patients, showed that poor motor imagery ability as measured by subjective vividness questionnaires was not associated with poor performance also on *objective* imagery ability assessment. So although vividness scores suggested the patients had poor motor imagery, objective task performance in these stroke patients suggested that motor imagery was in fact intact. This situation could lead to the risk that clinicians when using only vividness scores could dismiss patients as poor imagers and therefore unable to benefit from mental practice-based rehabilitation, while the patients' imagery ability would be deemed intact if measured in other ways. Although Lawrence et al. (2013, this issue) report that high motor imagery vividness is associated with an increased benefit of mental practice in novice gymnasts compared to the lower performance gains in those with low motor imagery vividness, this relationship may not be a simple one suitable for rehabilitation treatment decisions.

This research topic aimed to address confusion regarding the concepts of imagery and observation which has hampered the progression of mental practice research both scientifically and in translation to clinical practice. Wondrusch and Schuster-Amft (2013, this issue) remarkably point to the need to address any confusion regarding mental practice even at a therapeutic level. They advocate a good understanding of theory and practice in recipients using mental practice rehabilitation techniques by describing ways to teach stroke patients mental practice. Other contributions in this issue broaden the concept of mental practice in a number of ways, such as Howatson et al.'s rationale for including the observation of one's own movements within the mental practice concept (Howatson et al., 2013, this issue), Smith and Wakefield's considerations with regards to the timing rate of mental practice (Smith and Wakefield, 2013, this issue), Kirsch et al.'s link between action simulation and aesthetic experience (Kirsch et al., 2013, this issue), Schack et al.'s novel theory of how mental practice develops cognitive mental representation structures (Schack et al., 2014, this issue), and importantly Vogt et al.'s meticulous review of the evidence of why mental practice should encompass both motor imagery and action observation (Vogt et al., 2013, this issue).

Because neuroimaging studies provide strong evidence for action simulation, but the link to behavioral change is perhaps weak, we invited contributions to show that mental practice efficacy might be driven by neuroplasticity processes evoked by action simulation. The preliminary work by Olsson and Lundstrom (2013, this issue) shows that successful action anticipation, as a precursor of mental practice, appeared associated with motor and temporal regions of the brain. Future research needs to investigate evidence of the associations between mental practice performance benefits and brain plasticity in the motor network. It is possible that combination of techniques is needed, including functional magnetic resonance imaging (fMRI), diffusion tensor imaging (DTI), MEG, and EEG.

In conclusion, in an attempt to build on interdisciplinary consensus on the nature and application of mental practice, this research topic integrated perspectives from the full range of the disciplines involved in mental practice research. It furthermore intentionally did not seek to limit mental practice to a narrow interpretation of conscious mental rehearsal of movement or motor imagery, but instead advocates to include imitation and action observation of self or others as an interpretation of mental practice as Action Simulation Therapy (AST). Such an interpretation of AST mental practice is justified in light of the evidence for neural equivalence. What the neuroscience of neural equivalence means for our understanding of behavior, mechanisms, and applied efficacy of mental practice, however, needs a much more sustained research effort devoid of complacency and supported by high-risk-high-gain research funding. With this shared and funded research drive it will be possible to accelerate our understanding and agreement on the core processes of mental practice, and therefore speed up the translation of evidence-based benefit of applied use of mental practice in sport and clinical practice.

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Kinesthetic imagery training of forceful muscle contractions increases brain signal and muscle strength

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The purpose of this study was to compare the effect of training using internal imagery (IMI; also known as kinesthetic imagery or first person imagery) with that of external imagery (EMI; also known as third-person visual imagery) of strong muscle contractions on voluntary muscle strengthening. Eighteen young, healthy subjects were randomly assigned to one of three groups (6 in each group): internal motor imagery (IMI), external motor imagery (EMI), or a no-practice control (CTRL) group. Training lasted for 6 weeks (∼15 min/day, 5 days/week). The participants' right arm elbow-flexion strength, muscle electrical activity, and movement-related cortical potential (MRCP) were evaluated before and after training. Only the IMI group showed significant strength gained (10.8%) while the EMI (4.8%) and CTRL (−3.3%) groups did not. Only the IMI group showed a significant elevation in MRCP on scalp locations over both the primary motor (M1) and supplementary motor cortices (EMI group over M1 only) and this increase was significantly greater than that of EMI and CTRL groups. These results suggest that training by IMI of forceful muscle contractions was effective in improving voluntary muscle strength without physical exercise. We suggest that the IMI training likely strengthened brain-to-muscle (BTM) command that may have improved motor unit recruitment and activation, and led to greater muscle output. Training by IMI of forceful muscle contractions may change the activity level of cortical motor control network, which may translate into greater descending command to the target muscle and increase its strength.

Keywords: motor imagery training, muscle strength, electroencephalography (EEG), movement-related cortical potential (MRCP)

INTRODUCTION

Accumulating evidence suggests that mental training without physical or muscle exercise can improve voluntary muscle strength (Yue and Cole, 1992; Yue et al., 1996; Smith et al., 2003; Zijdewind et al., 2003; Ranganathan et al., 2004; Sidaway and Trzaska, 2005; Shackell and Standing, 2007). This finding could have significant application in rehabilitation medicine (Jackson et al., 2001) because numerous weak patients or frail older adults who find it difficult or unsafe to participate in conventional strength training (such as weightlifting) programs, may now be able to strengthen their muscles by using their mind. It has been shown that the main underlying mechanism for motor imagery (MI) training-induced strength gains is by adaptations occurring in the nervous system. For example, after 4 weeks of mental training, the strength of the little finger abduction force increased 22%; the augmentation accompanied an increase in the electromyographic (EMG) signal of the finger abductor that represented overall neural input to the muscle (Yue and Cole, 1992). In another study, two groups of volunteers had their little finger of the left hand immobilized for 4 weeks during which one group performed MI training of maximal voluntary contractions (MVC) and the other [control (CTRL) group] did not. After immobilization, both groups showed muscle atrophy but strength reduction only occurred in the CTRL group. The MI group maintained the strength with a significant increase in the EMG signal despite muscle atrophy caused by immobilization (Yue et al., 1996). In this case, the increase of neural (EMG) signal appeared to compensate for strength loss due to the atrophy. More recently, Ranganathan et al. (2004) demonstrated MI training-induced strength gains in a finger and upper-arm muscle that accompanied an elevation in the cortical signal directly related to the execution of strength-production muscle contractions. These observations support the hypothesis that the descending command from the brain to target muscle for MVC can be strengthened by MI training alone, which in turn increases maximal muscle force by recruiting additional motor units and/or increasing activation level of the participating motor units.

Despite finding of significant strength gains by MI training in a majority of studies in this area, one investigation (Herbert et al., 1998) did not reported similar results. In this study, no significant strength gain specifically associated with MI training was observed following an 8-week training program. The discrepancy in the results between this (Herbert et al., 1998) and other MI strength training studies could have been caused by different imagery procedures adopted by the investigators. There are two common types of mental imagery—internal and external imagery. In internal imagery (IMI; also known as kinesthetic or first-person imagery), a person imagines or mentally creates the feeling of performing the exercise from within the body (i.e., from a first-person perspective). For example, mental strength training using internal imagery emphasizes that the subject generates a similar feeling as he/she felt during a physical MVC (e.g., Ranganathan et al., 2004; Sidaway and Trzaska, 2005). In external imagery (EMI; also known as third-person visual imagery), the person sees or visualizes performing the task from outside the body—similar to watching oneself in a mirror performing an exercise (i.e., from a third-person perspective). Performing IMI generates significantly more physiological responses [such as heart rate (HR), blood pressure (BP), and respiration rate] compared to doing EMI (Ranganathan et al., 2004). Many studies (Mumford and Hall, 1985; Murphy, 1994; White and Hardy, 1995; Reed, 2002) have indicated that IMI is superior to EMI for improving motor skills. Studies have reported that highly skilled athletes predominantly use IMI to enhance their performance (e.g., Roure et al., 1998). It is possible that participants in the study of Herbert et al. (1998) adopted EMI procedure for the mental training, which did not result in a significant strength gain. For those studies that demonstrated significant strength increases, the MI training procedure was clearly using IMI (Yue and Cole, 1992; Yue et al., 1996; Smith et al., 2003; Zijdewind et al., 2003; Ranganathan et al., 2004; Sidaway and Trzaska, 2005; Shackell and Standing, 2007). However, no studies have attempted to compare the effects of two (internal and external) imagery training regimens on muscle strengthening. The purpose of this study was to compare strength gains following the two mental training programs: IMI and EMI.

METHODS

SUBJECTS

Eighteen right-handed young (18–35 years) and healthy volunteers were recruited and randomly assigned to three groups: internal motor imagery (IMI), external motor imagery (EMI), and no-practice CTRL groups. None of the subjects had participated in any regular exercise program for at least a year prior to the study. The training lasted for 6 weeks (15 min/day for 5 days/week). The Institutional Review Board at the Cleveland Clinic approved the study and all participants gave their informed consent prior to participation.

TRAINING PROTOCOL

Subjects in the IMI group imagined performing the task from a first-person perspective, i.e., they visualized and feel as if they were physically executing a maximal elbow-flexion contraction (Ranganathan et al., 2004). During each trial, they were instructed to imagine their forearm pushing maximally upward against the force transducer that was used for the strength measurements during the pre-training tests or against a heavy object. In other words, they *urged* the elbow-flexor muscles to contract maximally during each training trial. Some participants visualized putting the forearm under a heavy table and then tried very hard mentally to lift the table. Subjects could see the stationary arm held on the side of the body when imagining the contraction even though many subjects performed the mental exercises with their eyes closed. This same IMI protocol was found to significantly elevate HR and BP in a prior study (Ranganathan et al., 2004). Subjects in the EMI group viewed (in their mind) themselves performing the elbow flexion task from a third-person perspective, i.e., they watched themselves performing the task in their mind without a strong intent to make the contraction. In each 15-min training session, subjects performed 30 training trials, ∼15-s per trial followed by a 15-s rest. EMG signals from the two elbow flexor muscles, biceps brachii, and brachioradialis that are accessible from skin surface were viewed in every trial and session and recorded randomly in some trials and sessions to monitor activity level of the target muscles. On average, the EMG amplitude during the IMI and EMI training was less than 2% EMG for the MVC performed during the pre-training strength test (see below) and did not differ between the two training groups.

FORCE (STRENGTH) MEASUREMENT

Right arm elbow flexion force was measured by a force transducer (JR3 Universal Force-Moment Sensor System, Woodland, CA) with subjects seated, their right hand placed in a wrist cuff, forearm in a neutral position and an elbow joint angle of ∼ 100° (Ranganathan et al., 2004). The elbow was supported at hip height and the shoulders and torso were kept in position using restraints. Three elbow flexion MVC trials were performed in each measurement session and the highest force among the trials was analyzed. For each trial, participants were verbally encouraged to exert maximal force. Strength measurements were made before and after the 6-week training period. The strength measurement conditions (arm and body positions), and joint angles were carefully measured each time and maintained over the sessions. In addition, the verbal instruction and encouragement for maximal force production were the same for all measurement sessions. The force data was digitized at 100 samples/s using a data acquisition system (Micro 1401, Cambridge Electronic Design, Ltd., Cambridge, UK) and recorded on hard drive of a personal computer (PC).

EMG MEASUREMENT

Surface EMG was recorded during the elbow-flexion MVC force measurement trials using bipolar surface electrodes (Ag-AgCl, In Vivo Metric, Healdsburg, CA; 8-mm recording diameter and 2 cm apart of the two electrodes) from the belly of the biceps brachii (BB) and triceps brachii (TB) muscles. A reference electrode was placed on the skin overlying the lateral epicondyle near the elbow joint. Average BB EMG during a period when the MVC force was stable in each trial was calculated and the trial that yielded the highest average EMG was analyzed. The TB EMG during the elbow flexion MVCs was normalized to the TB EMG recorded during the elbow extension MVC and was a measure of the antagonist (TB) muscle activity during strength performance of the agonist (elbow flexor) muscle group. The EMG signal was amplified (× 1000) and band-pass filtered (3 Hz–1 KHz) using a Neurodata Amplifier system (Model 15A54, Grass Instrument Co., Quincy, MA), digitized (2000 samples/s) using the Micro-1401 system, and recorded on hard drive of the PC.

EEG AND MRCP MEASUREMENT

EEG electrodes were placed on the scalp roughly overlying the supplementary motor area (Cz), contralateral (C3) and ipsilateral (C4) sensorimotor regions, and central location of the frontal lobe (Fz). Electrode locations were determined based on the International 10–20 System (Jasper, 1958). Conducting gel (Electro-gel™, Electro-Cap International, Inc., Eaton, OH) was injected into each electrode to connect the recording surface of the electrode with the scalp. Impedance between each electrode and the skin was maintained below 5000 Ω (at 30 Hz). The EEG signal was amplified (× 20,000) and band-pass filtered (0.1–100 Hz) by the Neurodata Amplifier system, digitized (500 samples/s) using the Micro-1401 system, and stored on hard disk of the PC.

In each measurement session, the EEG recording was made after the strength and associated EMG data collection. Participants performed 30-elbow flexion MVCs (once every 20 s) during the EEG recording. The purpose of performing multiple MVC trials was to obtain triggered averaging of the MVC-related cortical potential (MRCP) with improved signal-to-noise ratio. Raw EEG data were visually examined, and trials with artifacts (such as eye blinks) were excluded. For each EEG-MVC trial, a 4-s window of the EEG was triggered by the force output (threshold = 5% initial MVC force), 2 s before and 2 s after the trigger (Siemionow et al., 2000; Fang et al., 2001). The triggered averaging (over the 30 trials) was performed by Spike 2 data analysis software (Cambridge Electronic Design, Ltd., Cambridge, UK) associated with the Micro-1401 system. The amplitude of each averaged MRCP was measured from the baseline to the peak of the negative potential (to view the shape of MRCP and its measurement, see Figures in: Siemionow et al., 2000; Yue et al., 2000; Fang et al., 2001). Because the MRCP was time-locked to each MVC, it was considered directly related to the planning and execution of the MVC. It has also been shown that there is a direct linear relation between force strength, EMG signals during voluntary muscle activation, and the amplitude of MRCP (Siemionow et al., 2000). Thus, increases in MRCP amplitude after training can be considered a direct indication of an enhancement in the descending command to the target muscle (Ranganathan et al., 2004).

STATISTICAL ANALYSIS

One-Way analysis of variance (ANOVA) was used to test for group difference at baseline for all outcomes. For all analyzes, group (IMI, EMI, and CTRL) was chosen as the independent variable and percentage MVC, EMG, and MRCP changes from baseline as the dependent variables. The choice of using percentage change was made to adjust for inter-individual baseline difference. Within group comparison was first performed to test for significant percentage change using one group student t-test comparison. Then ANOVA was used to test for overall between group comparisons (equivalent to a group by time interaction) followed by *post-hoc* analyzes to perform pair-wise group comparison. Given the pilot nature of the study, to avoid Type II error significance levels are first presented without correcting for multiple comparisons. Implication of performing significance level adjustment using the conservative Sidak method is then presented and its implication discussed. Given the small sample size and thus, potential strong influence of small deviation from normality, sensitivity analysis was also performed by running non-parametric Kruskal-Wallis and Wilcoxon tests for overall and pair-wise group comparisons.

The level of significance was set at 0.05 for all statistical analyzes. Results are given as mean ± SE. All analyzes were conducted using IBM SPSS version 21 and Excel for simple t-test.

RESULTS

BASELINE COMPARISON

No significant between group differences were found for strength [$F_{(2,\ 15)} = 1.6$, $p = 0.23$], and BB [$F_{(2,\ 15)} = 1.22$, $p = 0.33$] and TB [$F_{(2,\ 15)} = 0.86$, $p = 0.44$] EMG.

CHANGES IN STRENGTH AFTER TRAINING

The IMI group had significant strength gains [mean ± SE, 10.8 ± 2.7%, $t_{(1,\ 5)} = 4.06$, $P = 0.01$] after the 6-week training while the change in strength in the EMI group after training was not significant [4.8 ± 4.3%, $t_{(1,\ 5)} = 1.13$, $P = 0.31$; **Figure 1**. Subjects in the CTRL group who did not perform training of either kind, had no strength gain [−3.3 ± 2.61%, $t_{(1,\ 5)} = 1.25$, $P = 0.27$]. Using ANOVA, a significant group effect was found on the percentage change in strength, $F_{(2,\ 15)} = 4.66$, $P = 0.03$. Compared to control, *post-hoc* tests reveal the improvement for IMI to be significant compared to control, $t_{(1,\ 15)} = 3.04$, $P = 0.008$ while for EMI the improvement was only marginal compared to control, $t_{(1,\ 15)} = 1.75$, $P = 0.10$. Group difference between EMI and IMI was not significant, $t_{(1,\ 15)} = 1.29$, $P = 0.22$.

Furthermore, all participants in the IMI group (compared to only 50% in the EMI group) showed clinically meaningful strength gains (defined as being of medium effect size based on Cohen's d definition i.e., percentage change greater than half the overall standard deviation which is equal to 9.6%). The between group difference in the percentage of participants who improved were close to significance ($P = 0.09$ using Fisher's exact test). The

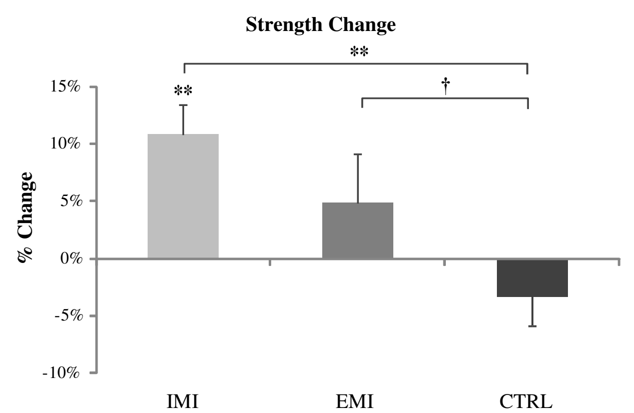

FIGURE 1 | Pre- to post-training percentage change in strength values for all three groups. Only the IMI group had a significant strength gain after training which was significantly greater than Control. EMI shows only marginal greater strength gain compared to Control. $^{†}P < 0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$.

strength results suggest that the IMI training can significantly improve maximal elbow flexor muscle force from baseline but the EMI training cannot.

CHANGES IN BB AND TB EMG

Along with increases in strength, muscle electrical activity (EMG) of the BB muscle increased by $38 \pm 26\%$ for the IMI group and by $27 \pm 19\%$ for the EMI group but due to the huge variation in EMG values across subjects (standard deviation of 65 and 47%, respectively), these increases were not significant [$t_{(5)} = 1.43$, $p = 0.21$ and $t_{(5)} = 1.42$, $p = 0.22$, respectively] (**Figure 2A**). The normalized TB EMG did not change significantly either with an increase of $6 \pm 11\%$ for IMI ($p = 0.58$) and decrease of $17 \pm 15\%$ for EMI ($p = 0.28$) (**Figure 2B**). The CTRL group had minimal changes in EMG before and after the training period (**Figure 2**). Similarly ANOVA showed no overall group effect for both percentage change in BB EMG [$F_{(2, 15)} = 1.22$, $P = 0.32$] and TB EMG [$F_{(2, 15)} = 1.21$, $P = 0.33$].

CHANGES IN MVC-RELATED CORTICAL POTENTIAL (MRCP)

Subjects in the IMI, EMI, and CTRL groups performed 30 MVC trials before and after training, and MRCP was derived by triggered-averaging of the EEG data associated with the MVCs. **Figure 3** shows MRCP percentage change for both the Cz and C3 locations. The baseline-to-peak MRCP value at Cz and C3 electrode locations significantly increased by $22 \pm 5\%$ [$t_{(5)} = 4.48$, $P = 0.007$] and $20 \pm 6\%$ [$t_{(5)} = 3.34$, $P = 0.02$], respectively for the IMI group, and $2.6 \pm 9\%$ [$t_{(5)} = 0.29$, $P = 0.79$] and $5.4 \pm 1.2\%$ [$t_{(5)} = 4.41$, $P = 0.007$] for EMI while the no-practice CTRL groups did not have any significant changes [$-6.2 \pm 5.6\%$, $t_{(5)} = 1.11$, $P = 0.32$ and $-2.1 \pm 4.0\%$, $t_{(5)} = 0.53$, $P = 0.62$]. Note that even though C3 MRCP changes for EMI were statistical significant, this was mainly the result of an unusual small variation in the data (std = 3.0). The amplitude increase (2.6%) was comparatively smaller than EMI (22%) and thus, could be considered marginal. A significant group effect for both the Cz and C3 locations was found by running ANOVA on the percentage MRCP changes [$F_{(2, 15)} = 4.59$, $P = 0.03$ and $F = 7.01$, $P = 0.01$, respectively]. *Post-hoc* analyzes revealed that MRCP increases for IMI were significantly greater than CTRL for Cz [$t_{(1, 15)} = 2.96$, $P = 0.01$] and C3 [$t_{(1, 15)} = 3.69$, $P = 0.002$] and significantly greater than EMI for C3 [$t_{(1, 15)} = 2.41$, $P = 0.03$] and marginally so for Cz [$t_{(1, 15)} = 2.04$, $P = 0.06$]. No difference existed between EMI and CTRL [$t_{(1, 15)} = 2$, $P = 0.37$ for Cz and $t_{(1, 15)} = 2$, $P = 0.53$ for C3].

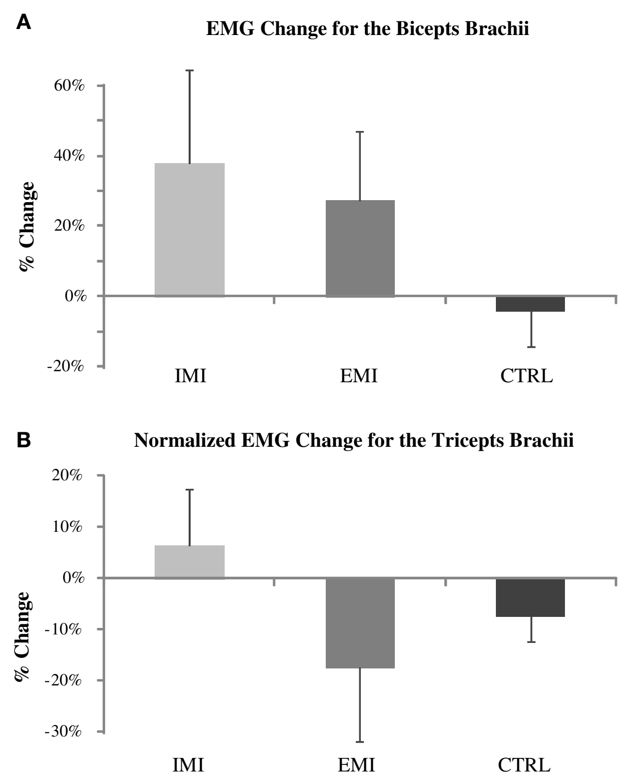

FIGURE 2 | Pre- to post-training percentage change in the biceps brachii (BB) average EMG (A) and normalized triceps brachii (TB) EMG (B) for IMI, EMI, and CTRL groups. The TB EMG during elbow flexion MVC was normalized to TB EMG during elbow extension MVC. The apparent BB EMG increases for the IMI and EMI training (upper panel) were not significant due to large data variations.

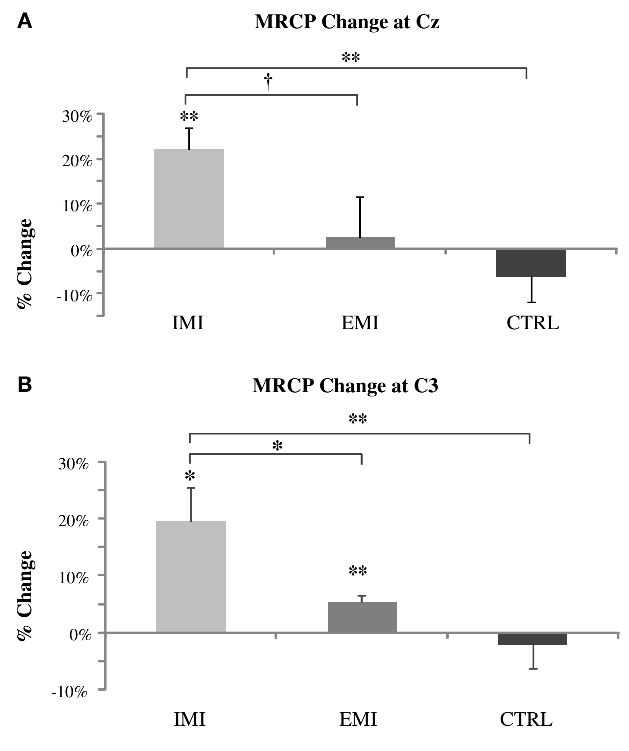

FIGURE 3 | Pre- to post-training percentage change in MRCP amplitude at Cz (roughly over the supplementary motor area) (A) and C3 (roughly over the contralateral sensory motor area) (B) locations. The IMI group had a significant increase in the MRCP amplitude at Cz and C3 and EMI at C3 only while no significant change was observed for CTRL groups did not. MRCP increases for IMI were significantly greater than control for Cz and C3 and greater than EMI for C3 and marginally so for Cz. EMI increases compared to Control were not significant. $^{\dagger}P < 0.1$, $^{*}P < 0.05$, $^{**}P < 0.01$.

The slope or rate of force production during the MVC performance (for MRCP measurement) was similar before vs. after training and between groups; this ensured that the difference seen in MRCP amplitude between the groups was not caused by a discrepancy in the rate of force development (Siemionow et al., 2000).

CORRECTION FOR MULTIPLE COMPARISONS AND SENSITIVITY ANALYSIS USING NON-PARAMETRIC TESTS

When performing significance level adjustment to *post-hoc* analyzes using the conservative Sidak method, results remained significant for all outcomes except for IMI within group change for Cz MRCP which became borderline significant ($P = 0.06$) and between group changes for IMI vs. EMI C3 MRCP which became non-significant ($P = 0.11$).

The non-parametric Kruskal-Wallis and Wilcoxon tests for overall and pair-wise group comparisons showed a similar pattern of significance than ANOVA and *t*-test providing confidence that results are not the product of statistical or data distribution anomalies.

DISCUSSION

The primary finding of this study was that training involving internal mental imagery of strong muscle contractions significantly improved voluntary muscle strength but external mental imagery of the same motor task did not yield such strength increase. The strength augmentation in the IMI group was accompanied by a significant elevation in the level of brain activation (MRCP) compared to the baseline and MRCP change experienced by the EMI group. It is worth noting that EMG signals from the major elbow flexor muscle was monitored during every training session and the muscle activity remained well below 2% maximal contraction level and no difference was found in the EMG activity level during the training between the two groups.

Our findings indicate that the central nervous system reacts to IMI and EMI training differently. While both methods require the subject's attention (with negligible physical activity), MRCP results suggest that the IMI activates motor cortical areas [perhaps somatosensory areas (SMA) and M1] more than external imagery, probably because the cortical centers try to recreate the kinesthetic feeling and generate a strong command during the imagery. We suggest that this process might reinforce the neural circuitry and send stronger signals to the target muscle. This hypothesis of differential mode of action between IMI and EMI seems to be supported by recent imaging studies. Similarly to our findings, it has been found that IMI more greatly implicates motor related areas such as cerebellum, SMA, dorsal premotor cortex, and cingulated motor area than EMI does (Ruby and Decety, 2001; Naito et al., 2002; Malouin et al., 2004). Furthermore, IMI shows greater activation in the parietal and more specifically the inferoparietal cortex (Ruby and Decety, 2001; Naito et al., 2002; Malouin et al., 2004), areas known to be implicated in the sensory-visual representation and preparation of movement (Fogassi and Luppino, 2005), and thus, more likely to be involved in the IMI process than EMI where there was no intention to create movement. Our findings and that of others indicate that IMI more greatly activates motor regions involved in the planning and execution of movement than EMI, providing potential neural mechanisms underlying strength gains observed only in IMI.

The strength improvements accompanied an increase in time-locked cortical potential. This finding suggests that repetitive strong intention to maximally activate the elbow flexors trained and enabled the relevant brain regions to generate stronger signals to muscle. The relatively consistent MRCP values in the CTRL group (**Figure 3**; no significant percentage changes) before and after training suggests that the MRCP measurement is reliable even across many sessions and a long period of time as found in our prior study (Ranganathan et al., 2004). Previous research (Dettmers et al., 1995; Siemionow et al., 2000; Dai et al., 2001) has shown a proportional relationship between magnitude of brain-to-muscle signal and voluntary muscle force by young human subjects, indicating that greater strength is a consequence of stronger brain activity. A descending command could recruit the motor units that were otherwise inactive in an untrained state and/or drive the active motor units to higher intensity (higher discharge rate), leading to greater muscle force. Alternatively, the trained control network may be able to more effectively remove or reduce inhibitory input to the motoneuron pool of the muscles, resulting in a net increase in motoneuron output. Training-induced neural adaptations may also include improvements in muscle coordination, such as reductions in the activity of the antagonist muscles when performing the agonist muscle MVC (Carolan and Cafarelli, 1992). However, our EMG result from the TB muscle, antagonist of the elbow flexors did not change after training, indicating that the antagonist muscle did not play a significant role in the elbow flexion strength gain.

The sample size of this pilot study was small (6 in each group). Nevertheless, the consistent results obtained using parametric and non-parametric methods as well as contingency analysis on the percentage of participants who improved force strength provide sufficient confidence on the results obtained in this pilot study. Future studies with larger sample size would need to replicate this study to confirm the results and in particular demonstrate statistical significance between IMI and EMI. There was no objective method to monitor cortical activities during internal and EMI performances. Identifying an accurate and reliable brain signal that can be monitored online would not only enable the performer to more correctly carry out a given imagery task, but the signal may also be used for other purposes such as controlling an assistive device for rehabilitation via brain-computer or brain-machine interface. Given the non-local nature of EEG signals, the contribution of far-field effect to the results observed at C3 and Cz cannot be ruled out. High density EEG data will be needed to confirm that the observed activity changes come indeed from the supplementary and sensorimotor regions. Furthermore, the possibility of doing mapping and source localization of cortical potentials with high density EEG recording could also provide more information about the differences and mechanisms underlying various imagery training approaches. Adoption of functional imaging such as fMRI or PET during imagery exercise may provide additional information regarding location and activation level in the brain while performing internal imagery vs. external imagery tasks. Further research in this area is needed to overcome these limitations and better understand the differences in imagery perspectives and effect of various imagery training programs on strength and motor skill gains.

This study is the first to directly compare efficacies by IMI and EMI training regimes on muscle strength. Knowing that the IMI training is superior to EMI in gaining strength from baseline and generate greater descending command, the information is valuable to potentially provide guidance in implementing mental imagery training in clinical or sport environment. The findings have clinical importance to potentially adopt IMI training as a therapy to treat weakness in frail patients and older adults without undergoing intimidating conventional strength training.

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Performance improvements from imagery: evidence that internal visual imagery is superior to external visual imagery for slalom performance

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We report three experiments investigating the hypothesis that use of internal visual imagery (IVI) would be superior to external visual imagery (EVI) for the performance of different slalom-based motor tasks. In Experiment 1, three groups of participants (IVI, EVI, and a control group) performed a driving-simulation slalom task. The IVI group achieved significantly quicker lap times than EVI and the control group. In Experiment 2, participants performed a downhill running slalom task under both IVI and EVI conditions. Performance was again quickest in the IVI compared to EVI condition, with no differences in accuracy. Experiment 3 used the same group design as Experiment 1, but with participants performing a downhill ski-slalom task. Results revealed the IVI group to be significantly more accurate than the control group, with no significant differences in time taken to complete the task. These results support the beneficial effects of IVI for slalom-based tasks, and significantly advances our knowledge related to the differential effects of visual imagery perspectives on motor performance.

Keywords: mental practice, kinesthetic imagery, imagery ability, VMIQ-2, speed-accuracy tradeoff

INTRODUCTION

Research examining the effects of imagery on the acquisition and execution of motor performance has delineated imagery into modalities and perspectives. This delineation includes visual and kinesthetic sensory modalities (e.g., Hardy and Callow, 1999; Fourkas et al., 2006; Guillot et al., 2009), with the visual modality being further separated into two visual imagery perspectives. These two perspectives are: internal visual imagery perspective (IVI: where the imaginer is looking out through his or her own eyes while performing the action) and external visual imagery perspective (EVI: where the imaginer is watching him or herself performing the action from an observer's position; as if watching him or herself on television). Refer to Callow and Roberts (2012) for further detail surrounding visual imagery perspective conceptualization. The kinesthetic imagery modality is defined as how it feels to perform an action, and includes aspects such as the force and effort involved in movement (Callow and Waters, 2005).

Early research exploring the effect of internal and external visual imagery produced equivocal results. For example, Mahoney and Avener (1977) revealed that successful qualifiers for the U.S. Olympic gymnastics team used internal imagery more than non-qualifiers. However, in contrast to this, Ungerleider and Golding (1991) found that successful U.S. track and field athletes used more external imagery than non-successful athletes. In addition, some experimental studies (e.g., Epstein, 1980) found no differences between imagery perspectives and their effects on performance. Three possible explanations have been provided for these inconsistent results: (a) that specific visual imagery perspectives produce greater performance gains for certain motor tasks than for others (e.g., Highlen and Bennett, 1979; Hardy, 1997), (b) that previous conceptualizations of internal imagery (such as that used by Epstein and Mahoney and Avener) have confounded internal visual imagery with kinesthetic imagery (cf. Hardy and Callow, 1999), and (c) that it has been incorrectly assumed that kinesthetic imagery can only be experienced with an internal perspective or is easier to use with an internal perspective (cf. White and Hardy, 1995; Taktek, 2012).

Hardy and associates (White and Hardy, 1995; Hardy, 1997; Hardy and Callow, 1999) examined the task specificity explanation (part "a" above), and offered two hypotheses to explain the effects of different visual imagery perspectives on different motor tasks. In the first (EVI) hypothesis, they posited that EVI would be superior to IVI for tasks that require positioning the body relative to itself, such as tasks relying heavily on the use of "form." To test this hypothesis, White and Hardy (1995) examined the performance of a simulated rhythmic gymnastics routine following the use of either EVI or IVI. Results revealed that the EVI group made fewer accuracy errors in performance than the IVI group. Hardy and Callow (1999) confirmed this finding with a series of three ecologically valid tasks relying heavily upon the use of form for their successful completion. In all three tasks, (i.e., a karate kata task, a gymnastics floor routine, and a technical rock climbing task), the use of EVI was found to have a superior influence on performance compared to the use of IVI. Taken together these results provide support for Hardy's (1997) cognitive explanation for the EVI hypothesis. Specifically, Hardy suggested that imagery exerts a beneficial effect on performance only to the extent that the images generated supplement the information that is already available to the performer. Thus, for tasks relying heavily upon the use of form, EVI may be more useful than IVI because EVI would allow a performer to see the desired form associated with the correct movement.

In the second (IVI) hypothesis, Hardy and associates suggested that IVI would be superior to EVI for tasks that require positioning the body in relation to other external visual features, such as in slalom-based tasks where a performer has to follow a "line" through or around a set course (e.g., downhill slalom skiing), with the cognitive explanation (Hardy, 1997) that IVI may allow a performer to see the precise temporal and spatial locations where key movements need to be initiated (e.g., changing direction or "braking") from the actual viewing angle of the motor action in relation to external visual information. Thus, the temporal and spatial locations would be identified with reference to the performer's position on the actual line being taken, which would afford critical visuomotor information that would not be available or useful when using EVI.

To test the second hypothesis, White and Hardy (1995) used a wheelchair slalom task that required the participant to maneuver themselves through a set course of gates. The results showed that after initial practice on an acquisition course, participants using IVI completed a transfer trial with significantly fewer accuracy errors than participants using EVI. Therefore, use of IVI compared to EVI led to a more accurate performance, explained by participants being able to rehearse the responses required at each gate. However, the results also showed that EVI improved the speed at which the task was performed compared to IVI. White and Hardy suggested that these performance gains occurs because EVI allows participants to compare themselves with their own imagery, thereby enhancing their competitive drive. Following this line of reasoning, as IVI does not afford the comparison to the same extent as EVI, the motivation function is perhaps less evident for IVI. White and Hardy further discussed these findings in terms of a speed accuracy trade off *across* imagery perspectives, where IVI caused slow, but accurate performance and EVI caused a fast, but inaccurate performance.

More recently, a number of neuroimaging studies have shown differences in neural activity dependent on the imagery perspective taken (e.g., Ruby and Decety, 2001; Fourkas et al., 2006; Lorey et al., 2009). These neural differences have then been used to explain the differential effects of imagery perspectives on performance, via the notion of functional equivalence (e.g., Jeannerod, 1994, 2001; Hanakawa et al., 2008). That is, the more similar (functionally equivalent) the imagery of performance and the actual performance is, the more effective the imagery is at moderating performance (cf. Holmes and Collins, 2001; Smith et al., 2008; Wakefield et al., 2013). However, the conceptualization of imagery perspectives used in the neuroimaging studies differ markedly to both our conceptualizations of IVI and EVI, and the current received view in the sport psychology literature (e.g., Cumming and Ramsey, 2008; Moran, 2009; Tobin and Hall, 2012). For example, neuroscientific conceptualizations of internal imagery confound visual and kinesthetic modalities (e.g., Ruby and Decety, 2001; Lorey et al., 2009), and external imagery is usually of someone else (e.g., Ruby and Decety, 2001; Fourkas et al., 2006; Lorey et al., 2009). While several other fMRI (e.g., Guillot et al., 2009) and psychophysiological studies (e.g., Guillot et al., 2004) are clear to make distinctions between imagery modalities (i.e., visual and kinesthetic), these studies do not examine visual perspective differences. Consequently, a precise understanding of what neural areas are involved in internal visual imagery and external visual imagery is not known, and, thus the current neuroscientific research cannot be used to precisely explain the differential effects of *visual* imagery perspectives on performance. Having said this, we might assume similar neural functional equivalence between the specific visual imagery perspectives and the different tasks, with a slalom-based task being particularly moderated by internal visual imagery, or a form-based task being particularly moderated by external visual imagery (i.e., demonstrating specific functional equivalence; cf. Callow and Roberts, 2010).

The imagery perspective behavioral research literature already supports Hardy and associates EVI hypothesis, but support for the IVI hypothesis is not yet conclusive. In the present research we examined the IVI hypothesis by exploring the effects of IVI and EVI on three different slalom tasks; a driving-simulation slalom task in Experiment 1, a downhill slalom running task in Experiment 2, and a downhill ski-slalom task in Experiment 3. Although these tasks differ in their specific requirements, they all require a performer to follow a "line" through or around a set course in order to gain a fast performance time. We therefore suggest that IVI would be expected to be particularly beneficial in moderating performance for these tasks.

EXPERIMENT 1: DRIVING-SIMULATION SLALOM TASK

METHODS

Participants

A sample of 45 male participants was recruited (M age 21.35 = years $SD = 3.12$). The participants were all right-handed and had normal or corrected-to-normal vision. All participants held a UK driving licence for a minimum of 1 year, but reported that they had never played the specified driving game used in the experiment, and played computer games on average less than once per week in the preceding 6 months. All participants provided written informed consent, and ethical approval for the experiment was granted by the School's Ethics Board.

Experimental apparatus and task

The driving-simulation slalom task was undertaken in a purpose-built driving simulator, incorporating a rally car seat, a force feedback steering wheel (which could be turned ±900° to keep the car on the circuit), 6-speed gear shifter and pedals. The driving simulator was connected to a 22 inch LCD monitor displaying the Gran Turismo 5 Prologue game (Codemaster, Warwickshire). In a training phase of the experiment, the track used was the Suzuka Circuit, which was 3.61 miles long and consisted of 20 bends (nine left and 11 right). In the experimental phase, the chosen track was the Eiger Nordward circuit, which is 1.51 miles long and consists of 11 bends (five left and six right). In both phases, the circuits were driven as a time trial in dry, daylight conditions, with a Citroen C4 2.0 VTS Coupe'05 as the test car. The virtual reality display presented the driver's view out through the front window of the car as if actually driving the car.

Experimental phases

In order to train the participants to use the apparatus for the experimental phase, participants completed a 90-min training phase period where they had to achieve two criteria (derived from pilot testing). This included the completion of three consecutive laps under 170 s and a plateau in performance, where the last three lap times fell within 5 s of each other (cf. Wilson et al., 2007). If participants achieved the criteria, they then proceeded to the experimental phase. In the experimental phase, participants completed a total of 15 laps (five practice, five pre-imagery, five post-imagery) of the simulated rally driving circuit, with average lap time at pre and post-imagery condition used as the measure of change in performance. The participants were randomly assigned to one of three groups; internal visual imagery (IVI), external visual imagery (EVI), or maths-control. Following practice and pre-imagery performance measures, participants in the imagery groups were given an imagery script pertaining to the imagery group to which they were allocated. The IVI script detailed the task from a first person visual perspective, requiring the participants to image the task through their own eyes. The EVI script detailed the task from the perspective of a third person visual perspective, requiring the participants to see themselves performing the task. All scripts were developed using Lang's (1984) guidelines for including stimulus, response and meaning propositions into the script, and pilot tested (and amended based on feedback) prior to data collection. In order to maintain experimental control, the scripts were developed by the authors. However, there was flexibility in the scripts (e.g., participants in the IVI group were asked to imagine their view change as they turned a corner). This flexibility allows participants to develop their own images, thus providing a degree of individualization, and consequently the images being meaningful for the participants (cf. Wilson et al., 2010). The scripts took ~120 s to administer. Example excerpts from the scripts are as follows:

> (Example 1, IVI.) Crossing the start line, you see the long straight in front of the car. Notice as the front of the car is going downhill slightly; it is traveling over a couple of horizons. As you approach the S-shape bend head, you see the line you want to take. As the car approaches the bend, you break to take the perfect line, turning first to your right and then quickly to your left, staying close to the bend, and accelerating after the bend.
>
> (Example 2, EVI.) As the car crosses the start line, see the long straight in front of it. Notice that the car is going downhill slightly and is traveling over a couple of little horizons. As you see the car approach the S-shape bend ahead, you see the line you want it to take. As the car approaches the bend, you see yourself allowing the car to break to take the perfect line, seeing yourself turn the wheel first to your right and then to your left, staying close to the bend, and accelerating after the bend.

In the control condition, participants were required to answer standard arithmetic questions (e.g., $14 + 4 + 6$). This type of active control group has been demonstrated to prevent the use of imagery during the experiment, but does not interfere with performance on the dependent variable (cf. Driskell et al., 1994; Callow and Hardy, 2005).

Measures

Time-taken to complete each lap was measured automatically (in seconds) by the Gran Turismo 5 Prologue software, and recorded by the experimenter. Note that the line of driving moderated the time, with cutting corners reducing the time compared to driving in the center of the road, but with collisions with curbs, or driving on the grass adding to the time. In order to determine participants' imagery ability, all participants completed the Vividness of Movement Imagery Questionnaire-2 (VMIQ-2: Roberts et al., 2008). The VMIQ-2 has demonstrated acceptable factorial validity, construct validity and concurrent validity (see Roberts et al., 2008). The VMIQ-2 comprises 12 items that assess the ability to image a variety of movements. Participants are required to image each item using IVI, EVI, and kinesthetic (Kin) imagery, and rate the vividness of the image produced on a five-point Likert scale from 1 (*perfectly clear and vivid*) to 5 (*no image at all*). Cronbach's alphas for the current study were 0.86 (EVI), 0.90 (IVI), and 0.84 (Kin). A manipulation/social validation questionnaire was also administered. The first question, asked all participants whether they had been able to adhere to the treatment group. The remaining questions were only given to participants in the two visual imagery groups, and they were asked whether they had experienced any switching of visual imagery perspectives during the task, and whether they had experienced any kinesthetic imagery during their use of visual imagery. An 11-point Likert scale ranging from 0 (*not at all*) to 10 (*very much so*) was employed.

PROCEDURE

One week prior to the commencement of the experiment, participants completed the VMIQ-2. All participants achieved a criterion of equal to or less than 36 on each of the VMIQ-2 subscales, indicating that their imagery ability was *at least moderately clear and vivid*. Participants attended the laboratory individually and were instructed that the purpose of the experiment was to examine driving ability under different conditions. The experimenter read standardized instructions detailing the training and experimental phases to the participants. Participants then completed the 90 min training phase, and all participants achieved the criterion level. On completion of the training phase, participants were given a 15 min break before commencing the experimental phase. The experimenter read standardized instructions explaining that they were to complete a number of trials as fast as they could; five practice trials, then five pre-imagery test trials and then five post-imagery test trials[1]. Before each of the post-imagery test trials, participants in the IVI and EVI groups listened to a recording of the imagery script detailing the driving task from the visual imagery perspective to which they were assigned, and were asked to use the imagery prior to performing each of the trials. Participants in the control group solved 10 maths questions prior to each post-test trial, as pilot testing had revealed that the calculation of 10 maths questions equated to the average time taken to complete the imagery scripts. Upon completion of each post-imagery test trial, participants rated the extent to which they drove as fast as they possibly could on an 11 point Likert

[1] Standardized instructions can be obtained from the first author.

scale from 0 (*not at all*) to 10 (*very much so*), with the intent that any participant who scored less than 5 would be asked to repeat the trial. In the event, no participants scored less than 5 for any trial. At the end of the post-imagery test trials, participants completed the manipulation/social validation questionnaire. On completion of the questionnaire, the participants were de-briefed as to the nature of the experiment and thanked for their participation.

RESULTS

Preliminary analyses

All participants reported on the manipulation/social validation questionnaire that they were able to adhere to their allocated groups with minimum reported switching of perspectives in either of the imagery groups (i.e., a score of less than 3 was used at the cut-off criteria indicated that participants rarely, if at all, switched between IVI and EVI when they were only supposed to be using one perspective). Therefore, no participants were removed from the analysis. Participants in the IVI and EVI groups reported some experience of kinesthetic imagery during their visual imagery (see **Table 1** for descriptive results), although there was no significant difference between the imagery groups in terms of their kinesthetic imagery experience ($p = 1$, $d = 0$). Analysis of the VMIQ-2 data (using a bonferroni adjusted α of 0.017) revealed no differences between the different participant groups for IVI imagery ability $F_{(2, 42)} = 0.42$, $p = 0.66$, $\eta^2 = 0.02$ 1-β $= 0.11$, and kinesthetic imagery ability $F_{(2, 42)} = 1.32$, $p = 0.28$, $\eta^2 = 0.01$ 1-β $= 0.27$. However, for EVI imagery ability, there was a significant difference between the groups $F_{(2, 42)} = 7.48$, $p = 0.002$, $\eta^2 = 0.26$ 1-β $= 0.93$, with the EVI group showing significantly better EVI ability than the IVI group ($p = 0.003$, $d = 1.66$) and the control group ($p = 0.009$, $d = 1.45$).

Performance score (time-taken)

A mixed-model (group × test) ANOVA was employed to analyse the average lap-time at pre and post-test. Box's *M* test for homogeneity of dispersion matrices was significant. Data transformations failed to rectify this problem. However, Stevens (2002) states that if Box's *M* test is significant with approximately equal numbers in each group, the Type I error rate will only be slightly affected, whereas power will be weakened. Thus, it remains relatively safe to interpret significant effects, because they are robust enough to show significance despite the low power. Consequently, the results from the analysis on the raw (non transformed) data are reported here. The analyses revealed no significant main effect for group, $F_{(2, 42)} = 0.23$, $p = 0.80$, $\eta^2 = 0.01$ 1-β $= 0.08$, a significant main effect for test $F_{(1, 42)} = 18.57$, $p < 0.001$, $\eta^2 = 0.21$, 1-β $= 0.99$ and a significant group by test interaction, $F_{(2, 42)} = 13.65$, $p < 0.001$, $\eta^2 = 0.31$, 1-β $= 0.99$. Tukey's tests on the significant interaction revealed that there was no significant difference between groups at pre-imagery tests. However, at post-imagery tests, the internal visual imagery group performed significantly better than the external visual imagery group $q_{(42)} = 6.31$, $p < 0.05$, $d = 0.66$ and the control group $q_{(42)} = 6.94$, $p < 0.05$, $d = 0.63$. In addition, the IVI group significantly improved performance from pre to post-test $q_{(14)} = 9.56$, $p < 0.05$, $d = 0.98$. No other differences were significant. See **Table 1** for descriptive results.

Given that kinesthetic imagery can cause performance gains over and above those caused by visual imagery (Hardy and Callow, 1999), it was important to establish if the kinesthetic imagery used in the two conditions could have influenced the results (despite there being no significant differences in the experience of kinesthetic imagery in the two visual imagery groups). We examined the relationship between kinesthetic imagery and performance and found no significant correlation between kinesthetic imagery (reported from the manipulation/social validation questionnaire) and performance (average lap-time) at post-imagery test ($r_s = 0.06$, $p = 0.77$). Thus, the superior performance for the IVI group could not be attributed to differences in kinesthetic imagery experience between the two groups.

Table 1 | Kinesthetic experience and lap-time (seconds) at pre-test and post-test in Experiment 1.

Group	Kinesthetic experience *M* (*SD*)	Pre-test lap time *M* (*SD*)	Post-test lap time *M* (*SD*)
IVI	4.43 (3.00)	88.08 (2.10)	86.23 (1.78)
EVI	4.53 (3.02)	87.55 (1.94)	87.45 (1.92)
Control	–	87.67 (2.10)	87.57 (2.41)

DISCUSSION

The results of this first experiment offer clear support for the hypothesis that internal visual imagery appears superior to external visual imagery in a driving-simulation slalom task. Further, although there was no relationship between kinesthetic imagery and performance, contrary to previous debate that kinesthetic imagery cannot be used with external visual imagery (cf. Collins and Hale, 1997) the results provide further evidence that kinesthetic imagery can be experienced with both internal visual and external visual imagery. The theoretical and applied implications of the findings are discussed later in the General discussion section.

EXPERIMENT 2: DOWNHILL SLALOM RUNNING TASK

Although Experiment 1 used methods and procedures that afforded substantial experimental control, the participants were not actually moving through the visual field while performing the task, as they would do in sports such as canoe slalom and slalom skiing. It therefore could be argued that the findings of Experiment 1 alone lack in ecological validity. In Experiment 2, we aimed to replicate and extend Experiment 1 by using a more ecologically valid task. This involved downhill slalom running where participants actually moved through the visual field while completing the task. In addition, the task allowed for separate measures of time taken (as in Experiment 1) and accuracy (as reported in White and Hardy, 1995).

We *a* priori hypothesized that the use of IVI would produce superior performance in comparison to EVI. This hypothesis was partly based on the results of Experiment 1, and also based on two further arguments. Firstly, IVI involves the rehearsal of precise changes in direction at particular spatial positions (for example, the angle at which to change direction to move past a cone or object), helping participants to plan and select the best line. We propose that this rehearsal may help the participants to better plan and execute the slalom line during the task performance.

The second reason for expecting IVI to produce superior performance compared to both EVI was due to task differences between the current task of downhill slalom running and the wheelchair slalom task used by White and Hardy (1995). More specifically, as White and Hardy's wheelchair slalom task relied heavily on the *generation* of speed (because participants performed the task on a flat surface), the motivational function of EVI might have reduced the time taken, via enhanced competitive drive. In contrast, downhill slalom running relies more heavily on the *control* of speed (due to the effect of momentum) rather than speed generation. Thus, the motivational function of EVI would likely be less relevant.

METHODS

Participants

A sample of 22 sports science students (M age = 22.50 years, $SD = 3.08$; 18 men, four women) was recruited for the experiment. All participants provided written informed consent, and ethical approval for the experiment was granted by the School's Ethics Board.

Tasks and experimental conditions

The experiment consisted of a practice and an experimental task. In both tasks participants completed a downhill slalom running course, performance was measured in terms of time-taken and the frequency of cone touches (accuracy). The practice and experimental slalom courses were performed outdoors on a disused road that sloped downhill at an angle of 5°. Both courses were 55 meters in length and used 13 cones and automatic timing gates placed at the top and bottom of the course. The actual setup of the courses differed substantially. On the practice course, the cones were placed at reasonably long intervals, allowing participants to make wider (and less extreme) turns. In contrast, the experimental course required the participants to make more extreme changes in direction. Cones were placed much closer together, and on narrower angles, requiring "tighter" turns in order to be able to maintain a good line through the cones and to be able to complete the task quickly.

A repeated measures design was employed whereby participants completed the task in IVI and EVI conditions. The conditions were completed over two consecutive days and the order was counterbalanced across participants. In each condition, participants were administered a recorded imagery script that corresponded to their condition prior to completing the experimental task trials[2]. Scripts were developed using the same procedures and principles used in Experiment 1.

Measures

Using automatic timing gates placed at the top and bottom of the course, the time taken (in seconds) to complete each trial was recorded. To measure accuracy, an independent judge visually observed and then recorded the frequency of cone touches by participants for each trial. As with Experiment 1, imagery ability was measured using the VMIQ-2, and a manipulation/social validation questionnaire administered to assess adherence to the conditions, switching of visual imagery perspectives, and experience of kinesthetic imagery during the use of visual imagery.

PROCEDURE

The VMIQ-2 was administered 1 week prior to the commencement of the experiment, and all participants achieved the criteria used previously in Experiment 1. Participants were tested individually and on arriving at the experimental site, were equipped with wrist and hand protectors and sports clothing to cover all of the body. The equipment served as protection in case any participants fell while running. Participants were told that the purpose of the experiment was to examine the effects of different imagery scripts on a motor performance task. Standardized instructions were read informing the participants to complete the task as quickly and accurately as possible. Participants performed five practice trials on the practice course and were given a 3 min rest between trials. At the end of the practice trials, participants were given a 5 min break. Participants then entered the experimental phase of the experiment. Prior to performing the first experimental trial, participants were read the same standardized instructions as before, and were allowed to look at the new course and walk down the side of it. Participants were administered the relevant imagery script and were asked to employ imagery before completing each of two experimental trials. Only two experimental trials were employed (compared to five in Experiment 1), because this is the number of competitive trials that are performed in sports such as Super G in alpine downhill skiing and canoe slalom. At the end of each experimental trial, to ensure that the participants complied with the instructions, participants were asked to rate to what extent they ran as fast as possible down the course, on an 11 point Likert scale from 0 (*not at all*) to 10 (*very much so*). As with Experiment 1, no participants scored below five. On completion of the second experimental trial, a manipulation/social validation questionnaire was completed. The questionnaire examined the extent to which participants adhered to their treatment conditions, the experience of kinesthetic imagery, and the extent to which they switched between imagery perspectives. These questions were scored on the same Likert scale used in Experiment 1.

The participants returned the following day and performed the exact same procedure; though used the other imagery perspective. In the second day, following completion of the manipulation/social validation questionnaire, the participants were debriefed as to the nature of the experiment and thanked for their participation.

RESULTS

Preliminary analyses

To control for potential carryover effects as a result of the repeated measures design, a strict exclusion criteria was employed (Stevens, 2002). Participants were only retained for analysis if they were able to meet two criteria from the manipulation/social validation questionnaire. First, participants were required to be able to

[2]Scripts can be obtained from the first author.

report strong adherence to both the IVI and EVI conditions (as evidenced by adherence ratings of seven out of 10 or above for each imagery condition). Second, participants had to report minimal switching between imagery perspectives during each imagery condition (i.e., a score of less than 3 for each condition which would indicate that participants rarely, if at all, switched between IVI and EVI during a particular imagery condition when they were only supposed to be using one perspective). These criteria resulted in the data from 11 of the 22 participants being retained for analysis. Analyses showed that there was no difference in imagery ability across perspectives for these participants, $t_{(10)} = 1.06$, $p = 0.31$, $d = 0.45$.

Performance data

A dependent *t*-test was employed to examine the effects of the visual imagery perspective in the experimental trial that the participants ran the fastest in. Results revealed a significant difference for condition, $t_{(10)} = -3.29$, $p < 0.008$, $d = 0.42$. Inspection of the cell means revealed that the course was completed significantly quicker in the IVI condition than in the EVI condition (See **Table 2** for descriptive results). A statistical analysis of accuracy was not possible as none of the participants touched a cone in either of the conditions.

The results support the hypothesis, showing that IVI produced performance gains over EVI. This performance effect was shown via a reduction in time taken. In addition, there was no detriment to accuracy that is participants did not compromise accuracy, at least by colliding with the cones on spatially close turns, in order to achieve the lower times. This leads to the interpretation that the effect for time taken for IVI was not a result of a speed-accuracy trade-off across imagery perspectives. Further to this, and in line with Experiment 1, we wanted to confirm that the quicker times were not a result of greater kinesthetic imagery experience in the IVI condition. Participants reported (via the social validation/manipulation questionnaire) that they experienced kinesthetic imagery in both IVI and EVI conditions, although there was no significant difference between kinesthetic imagery experience in the two conditions ($p = 0.14$, $d = 0.38$). Further the experience of kinesthetic imagery was uncorrelated with performance ($r_s = 0.006$, $p = 0.98$).

DISCUSSION

The results of Experiment 2 replicate the findings of Experiment 1 providing further support of the beneficial effects of IVI over EVI in an ecologically valid slalom based task for speed. Further, the quicker times in the IVI group were not to the detriment of accuracy, and are in line with our reasoning that IVI should help to plan the most effective line. These data also highlight that the motivational function of EVI offered by White and Hardy might be redundant in tasks where the emphasis is placed on the *control* of speed (such as driving and downhill running) rather than *generation* of speed.

The measurement of accuracy in Experiment 2 (i.e., touching the cones or not) might be perceived as rather crude. We argue that if participants chose a line that was closer to the cones at a turn, they may have more likely collided with the cone. However, this measure may not have been comprehensive enough to capture differences in accuracy of line (or trajectory) across the entire task. Consequently, a third experiment was conducted in order to explore both time-taken and accuracy, using a more comprehensive measure of accuracy.

Table 2 | Kinesthetic experience and time taken (seconds) in Experiment 2.

Condition	Kinesthetic experience *M* (*SD*)	Time taken *M* (*SD*)
IVI	6.18 (3.19)	15.19 (1.15)
EVI	5.10 (2.54)	15.70 (1.24)

EXPERIMENT 3: DOWNHILL SKI-SLALOM TASK

Experiment 3 explored the effects of different visual imagery perspectives on a more ecologically valid task aligned to slalom sporting performance (i.e., a downhill ski slalom task), than those used in Experiments 1 (a laboratory-based simulation slalom task) and 2 (an experimentally generated slalom task) that allowed for measures of time taken (as in Experiments 1 and 2) and accuracy (as in Experiment 2). Based on the rationale presented in Experiment 2, our *a priori* hypothesis was that IVI would produce superior performance for either time-taken or accuracy or both in comparison to EVI.

METHODS

Participants

A sample of 30 recreational skiers (*M* age = 24.79 years, *SD* = 4.77, 23 men, seven women) was recruited for the experiment. Although all participants could ski with their skis parallel, none had any experience of slalom skiing. All participants provided written informed consent, and ethical approval for the experiment was granted by the School's Ethics Board.

Task and experimental conditions

A slalom skiing task was performed twice on an outdoor artificial ski slope. The course sloped downhill at an angle of 20° and was 120 meters long with six gates. The specific course of the gates was set at an intermediate level by a qualified ski-slalom coach. Performance was assessed by the time taken to complete the course, and the accuracy of the line taken. Automatic timing gates were placed at the start and finish points of the course, and time taken to complete each trial was recorded. Each trial was videoed and an experienced ski-slalom coach blind to the nature of the experiment subsequently judged accuracy. Two criteria were used for judgments of accuracy: (a) closeness to the pole, and (b) choice of line. Each of these criteria was scored on a Likert scale from 1 (*far away from pole/very sharp change of direction*) to 10 (*just missing the pole/perfectly smooth change of direction*) and the average of these two scores was used for the accuracy measure.

Participants were allocated to an IVI, EVI, or a control group. The participants in the control group were given a series of light stretches. The participants in both imagery groups watched a brief video clip of a club level skier (not skiing the artificial ski slope) from either an internal visual or external visual perspective (the treatment matched to their imagery group perspective) and were then administered an imagery script. The imagery scripts were either from an internal visual or external visual imagery perspective depending on the group. The scripts instructed the participants to create an image of themselves skiing the course and directed them to create, in their image, the terrain, position of the poles, and the line that they should take[3]. The participants were instructed to employ imagery before each trial.

PROCEDURE

As with Experiments 1 and 2, imagery ability, using the VMIQ-2, was measured 1 week prior to the commencement of the experiment, with all participants achieving the specified ability criteria. Participants were then randomly assigned to groups, and to numbered bibs indicating the order in which they would each conduct the first experimental trial. Before the start of the experimental session participants were allowed a warm-up period of 20 min to ski. In three different rooms, participants were then shown the video from their respective imagery perspective group (solely to demonstrate the difference between an IVI and EVI perspective), or conducted light stretches if they were in the control group. During this time, the slalom course was erected. All participants were then allowed to walk and inspect the slalom course. This inspection lasted ∼10 min. The participants then assembled in the changing room and were called individually (in bib order) to start the experimental phase. At the top of the ski slope, participants in the imagery groups were then read the imagery script and were asked to image themselves skiing the course from the respective imagery perspective. Participants in the control group conducted light stretches. In addition to this, all participants were asked to ski as quickly and as accurately as possible. Each participant then completed his/her first trial. On average, there was 30 min between the inspection of the course and the participant's first trial. The second trial took place in reverse bib order, and again was conducted on average 30 min after the first trial. Prior to performing the second trial, again at the top of the slope, participants read the imagery script themselves and were asked to image themselves skiing the course from the respective imagery perspective or complete the light stretches if in the control group. Participants were reminded to ski as quickly and as accurately as possible. For both trials, no time restrictions were placed on the participant to complete the imagery. No practice runs or discussion between participants was allowed in the changing room or while inspecting the course, and at no point during the experiment did any participant watch another participant's performance.

On completion of both trials, all participants completed a manipulation/social validation questionnaire. The questionnaire assessed; adherence to the imagery perspectives, the perceived suitability of each imagery perspective for completing the task quickly and accurately, and the experience of kinesthetic imagery for the two imagery groups. These questions were all scored on a Likert scale from 1 (*not at all*) to 10 (*greatly*). Also, participants were asked to report if they had used any other strategies to aid performance.

[3]Scripts can be obtained from the first author.

RESULTS

Preliminary analyses

Two participants from the control group were unable to complete both trials, leaving a sample of 28 participants. All participants in the imagery groups reported being able to adhere to their required imagery perspective and none of the participants in the control group reported using imagery to aid their performance. Data screening revealed significantly skewed and kurtotic distributions, with two outliers (one from the EVI group and one from the control group). These data points were removed and the remaining data were normally distributed. The remaining 26 participants were used for the analyses (7 control group, 10 IVI group and 9 EVI group). There were no differences between the imagery groups in whether kinesthetic imagery was experienced ($p = 0.32, d = 0.55$) although both groups reported experiencing kinesthetic imagery (See **Table 3** for descriptive results). However, the use of kinesthetic imagery was uncorrelated with time taken ($r_s = -0.06, p = 0.81$) and accuracy ($r_s = 0.03, p = 0.90$). There were no differences in reported imagery ability (adjusted $\alpha = 0.025$) across the groups for both IVI ($p = 0.53$, $\eta^2 = 0.05$, $1\text{-}\beta = 0.15$) and EVI ability ($p = 0.93$, $\eta^2 = 0.004$ $1\text{-}\beta = 0.06$). The fastest of the two trials recorded was used in the data analyses.

Main analysis

Single factor ANOVAs revealed no difference between the groups for time-taken, $F_{(2,\ 23)} = 1.22$, $p = 0.32$, $\eta^2 = 0.10$, $1\text{-}\beta = 0.24$, but did reveal a significant difference for accuracy, $F_{(2,\ 23)} = 3.59$, $p = 0.04$, $\eta^2 = 0.24$, $1\text{-}\beta = 0.61$. A Tukey's follow up test indicated a significant difference between the IVI group and the control group, showing that the IVI group was more accurate than the control group ($p = 0.04$, $d = 3.57$). See **Table 3** for descriptive results.

DISCUSSION

The results of this experiment offer some support for the hypothesis that IVI would produce superior performance than EVI in slalom based tasks. In the present data, this was demonstrated in terms of accuracy, as the IVI group was more accurate than the control group (with a large effect), whereas there was no difference between the EVI group and the control group. In terms of performance time-taken, there was no significant differences between the groups. However, the IVI group was one second quicker than the EVI group, and three seconds quicker than the control group. These differences correspond to small and moderate effect sizes of 0.30 (IVI and EVI) and 0.66 (IVI and control), respectively (cf. Cohen, 1992). Considering the time

Table 3 | Kinesthetic experience, time taken (seconds) and accuracy (line taken) in Experiment 3.

Group	Kinesthetic experience *M* (*SD*)	Time taken *M* (*SD*)	Accuracy *M* (*SD*)
IVI	7.40 (1.43)	20.26 (4.10)	12.00 (1.94)
EVI	6.33 (2.45)	21.26 (2.78)	11.00 (1.73)
Control	–	23.36 (5.26)	9.86 (0.6)

and accuracy performance results together, the findings from Experiment 3 are consistent with our theorizing that IVI may aid performance by helping to plan and execute the most accurate line. However, in isolation from the other experiments, the findings from Experiment 3 should be viewed with caution due to the low number of participants tested. The theoretical and applied implications of these findings are discussed in the General Discussion that follows.

GENERAL DISCUSSION

The purpose of the present research was to re-examine Hardy's (1997) hypothesis that IVI will produce superior performance on slalom-based tasks compared to EVI or control conditions. Taken together, the results of the three experiments here provided support for the hypotheses set out in the present research. Specifically, there were significant performance benefits for the use of IVI compared to EVI in Experiments 1 and 2 (in terms of time taken) and significant accuracy performance benefits between IVI and control in Experiment 3 (where EVI was no better than control). Further, in Experiments 2 and 3, the differences in performance did not seem to be caused by a speed-accuracy trade-off *across* perspectives, as there were no differences between IVI and EVI for accuracy performance in Experiment 2, and no differences between IVI and the control group, for time taken in Experiment 3.

The main finding that IVI produced performance gains on these slalom-based tasks can be interpreted in line with the cognitive explanation provided by Hardy (1997), and that the neural activity in the IVI condition may be more functionally equivalent with the neural activity that occurs when performing the task in comparison to EVI (cf. Holmes and Collins, 2001; Ruby and Decety, 2001; Fourkas et al., 2006; Lorey et al., 2009). Clearly, as highlighted in the introduction, as the neural areas involved in IVI and EVI are not known, we can only propose a neural explanation. Future research that examines this issue would be particularly informative, as it would help to differentiate the neural pathways involved in the visual perspectives, and ratify the cognitive explanations that currently exist as to why visual imagery perspectives impact performance.

Importantly, the results from Experiments 2 and 3 do not provide evidence that a speed-accuracy trade-off across imagery perspectives was the cause of the performance differences (not previously controlled in White and Hardy, 1995). Specifically in Experiment 2, there was no significant differences between accuracy for the IVI and EVI conditions, and in Experiment 3, there was no significant difference in time taken between the IVI and control conditions. With this control, together these data provide the first evidence supporting the theorized benefits of IVI in slalom tasks. Indeed, these data, combined with the finding of White and Hardy (1995) and Hardy and Callow (1999) that EVI had more influence of form based performance than IVI, support the Hardy (1997) hypotheses.

An interesting additional finding in the current research was that participants reported using kinesthetic imagery regardless of imagery perspective being used, with no significant differences in the amount of reported experience between the IVI and EVI groups. These findings support the notion that kinesthetic imagery can be experienced with both visual perspectives (e.g., Glisky et al., 1996; Callow and Hardy, 2004). However, for the purpose of the present research aim, it is important to highlight that as well as no difference in the amount of kinesthetic imagery experienced between the conditions, there were also no significant correlations between kinesthetic imagery and performance in any of the experiments. As a note of interest for further investigation, previous research has reported additional performance gains for kinesthetic imagery over and above those produced by visual imagery for form-based tasks (Hardy and Callow, 1999). In the current paper, the lack of correlation between kinesthetic imagery and performance is perhaps surprising. It might be that the performance gains produced by kinesthetic imagery can only be evidenced with relatively high level performers, as measured in Hardy and Callow (1999). Thus, the lack of correlation here might be due to level of expertise of the participants on the tasks used in the present studies, and their inability to make effective or efficient use of kinesthetic imagery (cf. Hardy and Callow, 1999). In support of this contention, a recent functional magnetic resonance imaging (fMRI) study found sport experts to utilize kinesthetic imagery more efficiently (as inferred from significant blood-oxygen-level dependence response in the parahippocampus) than novices (Wei and Luo, 2010). Alternatively, the benefit of kinesthetic imagery over visual imagery might be specific to particular tasks, and based on the data here, not beneficial in slalom based tasks. We suggest that future studies should manipulate the variables of expertise, visual and kinesthetic imagery and types of task on measures of performance.

Related to the previous paragraph, we propose that it would be interesting to extend the hypotheses of Hardy (1997), and determine whether kinesthetic imagery shows specificity to particular tasks, as now demonstrated for IVI and EVI for slalom and form based tasks, respectively. Furthermore, how expertise (in both imagery ability and sport action skill) moderates the Hardy (1997) hypotheses would be of interest. In principal, the rationale provided by Hardy (1997), albeit rudimentarily, suggests that imagery modalities may prime specific actions based on similarities between the cognitive processes involved in imagining and executing specific skilled actions. Support for this explanation comes from behavioral studies coupled with neuroscience techniques (e.g., fMRI and Transcranial Magnetic Stimulation) that have examined the brain-pathways involved in imagery (cf. Moran, 2009 for a review), and the role that expertise plays in the use of imagery (Milton et al., 2008). This research generally shows that the cognitive processes differ for the different imagery modalities, and furthermore that the cognitive processes are moderated by the level of expertise of the participant.

In addition, we did not specify the angle participants should take when imagining from an EVI perspective. Although research has yet to examine whether angle of EVI affects performance, researchers (e.g., Fournier et al., 2008) have highlighted that athletes do use different angles. Manipulating angle of EVI is an obvious step for future research to consider in all imagery perspective studies (cf. Callow and Roberts, 2010). Furthermore, it would be interesting to evaluate whether moderating imaged gaze points within the internal visual imagery of a slalom task would also moderate actual performance. Finally, it is currently unknown whether supplementary sensory information such as vestibular or auditory perception moderate external and internal visual imagery in the same way. We propose that future studies manipulate additional sensory information when considering the relative roles of imagery perspective on performance.

Aside from these theoretical implications, the current experiment provides several applied implications. First, the importance of considering task characteristics when recommending to athletes which imagery perspective may be more beneficial to use is highlighted. Second, for tasks requiring an effective use of line, where a performer is required to make specific changes in direction at precise spatial locations, IVI appears to be the best imagery perspective to use to aid performance. Thus, IVI is a meaningful psychological skill for sport psychologists and coaches to develop, and for athletes to use when trying to achieve performance gains for slalom-based tasks. Third, some tasks require both form and changes in direction at precise spatial locations (e.g., a double straight-back somersault in gymnastics). With these types of task, switching between IVI and EVI might be relevant, though evidence to support the effective use of imagery switching is needed. Finally, other motor skills that do not rely so heavily on the use of form or line (such golf putting or dart throwing) might benefit equally from the use of IVI or EVI (see Roberts et al., 2010).

Certain strengths and limitations can be associated with the research presented here. Using manipulation checks in all experiments was a strength of the research, as it enabled greater experimental control (cf. Murphy and Jowdy, 1992). Employing specific imagery ability criteria, based on previous evidence (e.g., Callow et al., 2001), to accept or reject participants to the experimental phase of the studies was a strength of the research (cf. Goss et al., 1986). Further, the use of three experiments with three different tasks (that were conceptually and methodologically linked) with consistent results across the different experiments was a particular strength in relation to the general imagery literature that has traditionally relied on single studies (cf. Goginsky and Collins, 1996). Despite these strengths, there are some limitations that deserve comment. Through the use of manipulation checks to enhance experimental control, a substantial removal of participants was performed, particularly so in Experiment 2. Imagery research has previously been criticized for failing to use rigorous manipulation criteria, and so here, we felt that this approach was appropriate despite the large participant loss. Despite this removal, the remaining participant sample resulted in the hypothesized reliable effects suggesting that the conservative approach did not impact on the data. We therefore recommend that the approach is used in future related studies.

A second potential limitation of the present research was the inability to control participants' spontaneous kinesthetic imagery experiences. Although we propose that this did not influence the current findings as there were no differences in kinesthetic imagery experiences between the IVI and EVI groups and furthermore that kinesthetic imagery experience was not correlated with performance, future research may wish to explicitly control for kinesthetic imagery use. This may involve the inclusion of a kinesthetic imagery (only) condition, or it might be possible to inhibit kinesthetic imagery cognitive processes through the use of repetitive Transcranial Magnetic Stimulation (cf. Jung et al., 2008). For example, Guillot et al. (2009) found kinesthetic imagery to elicit bilateral activations of the inferior parietal lobule (BA10) as well as several motor-related regions (including the putamen, the caudate nucleus, and the cerebellar hemispheres). The application of rTMS to these brain areas may suppress kinesthetic imagery while visual imagery can still be used.

A third potential limitation relates to the measures employed. Specifically, although time-taken is a variable involved in the calculation of speed, we have not measured speed (i.e., distance/time). Further, the measure of accuracy in Studies 2 and 3 are crude. Consequently, due to possible measurement errors brought about by these limitations, the interpretations related to the speed-accuracy trade off do need to be viewed with caution. Future research plotting the spatial trajectory of the line performance, perhaps relative to a perfect line or relative to gate positions, using technology such as GPS tracking systems, would be worthwhile. With this, comparison across and within perspectives for the separate and combined effects of speed and accuracy could be made.

To conclude, the results of the present research provide evidence for the use of IVI to enhance the performance of slalom-based tasks, and enhance our knowledge in the area of imagery perspectives research.

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The comparison between motor imagery and verbal rehearsal on the learning of sequential movements

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Mental practice refers to the cognitive rehearsal of a physical activity. It is widely used by athletes to enhance their performance and its efficiency to help train motor function in people with physical disabilities is now recognized. Mental practice is generally based on motor imagery (MI), i.e., the conscious simulation of a movement without its actual execution. It may also be based on verbal rehearsal (VR), i.e., the silent rehearsal of the labels associated with an action. In this study, the effect of MI training or VR on the learning and retention of a foot-sequence task was investigated. Thirty right-footed subjects, aged between 22 and 37 years old (mean: 27.4 ± 4.1 years) and randomly assigned to one of three groups, practiced a serial reaction time task involving a sequence of three dorsiflexions and three plantar flexions with the left foot. One group ($n = 10$) mentally practiced the sequence with MI for 5 weeks, another group ($n = 10$) mentally practiced the sequence with VR of the foot positions for the same duration, and a control group ($n = 10$) did not practice the sequence mentally. The time to perform the practiced sequence as well as an unpracticed sequence was recorded before training, immediately after training and 6 months after training (retention). The main results showed that the speed improvement after training was significantly greater in the MI group compared to the control group and tended to be greater in the VR group compared to the control group. The improvement in performance did not differ in the MI and VR groups. At retention, however, no difference in response times was found among the three groups, indicating that the effect of mental practice did not last over a long period without training. Interestingly, this pattern of results was similar for the practiced and non-practiced sequence. Overall, these results suggest that both MI training and VR help to improve motor performance and that mental practice may induce non-specific effects.

Keywords: motor imagery, verbal rehearsal, mental practice, foot movement sequence, learning, retention

INTRODUCTION

In the context of motor learning, mental practice may be defined as the cognitive rehearsal of a physical activity in order to enhance performance in this activity (Jackson et al., 2001). Mental practice is generally based on motor imagery (MI), i.e., the mental simulation of an action without its actual execution. Research on mental practice based on MI as a strategy to improve motor performance goes back to the 1930s (e.g., Sackett, 1934) and since then the use of MI training has become widespread in sport settings. It has been shown that it is often better to perform mental practice than no practice and that physical practice combined with mental practice often lead to better results than physical practice alone (see Richardson, 1967a,b; Feltz and Landers, 1983; Driskell et al., 1994; Munzert and Lorey, 2013). Furthermore, there is accumulating evidence that mental practice based on MI can be efficient to help train motor functions in people with physical disabilities of neurological origin (see Dickstein and Deutsch, 2007; Malouin and Richards, 2010; Malouin et al., 2013). The use of mental practice in a rehabilitation setting appears particularly relevant as it provides a unique opportunity to practice different kinds of movements – even complex motor tasks – in an autonomous and safe manner while avoiding undue physical fatigue.

Concerning the underlying mechanisms of MI training, it has been repeatedly shown that MI recruits brain regions pertaining to the motor system (e.g., Decety et al., 1994; Gerardin et al., 2000; Malouin et al., 2003; Munzert and Zentgraf, 2009; Hetu et al., 2013). MI training would thus prepare the body to act by "priming" the brain regions involved in the execution of the action. Furthermore, similar brain plasticity has been demonstrated after physical training and mental training based on MI (Pascual-Leone et al., 1995; Jackson et al., 2003; Debarnot et al., 2011), indicating that both forms of training would involve similar neural mechanisms.

If mental practice generally refers to MI training, it has been proposed that mental practice based on verbal rehearsal (VR) – i.e., the covert repetition of verbal labels attached to different elements of an action – could also be useful to improve motor skills (e.g., Hall et al., 1997). Compared to MI training, however, the use of VR has received considerably less attention. Most of the studies that investigated the use of verbal labels to improve motor skills have explored self-talk strategies by athletes. Self-talk content may be categorized as either motivational or instructional (Theodorakis et al., 2000). Motivational self-talk refers to labels aimed at increasing confidence or motivation (e.g., "you can do it"), whereas instructional self-talk refers to labels aimed at directing attention toward movement cues (e.g., "reach, move right," etc.) and facilitating the learning of a skill (Zinnser et al., 2006). An important part of the research on self-talk with athletes focuses on its instructional role and it has been shown that the use of verbal labels in this context helps to learn different sport skills (e.g., Ziegler, 1987; Ming and Martin, 1996; Landin and Hebert, 1999). Self talk, however, is most of the time used by athletes in parallel with the movement they actually perform (Gammage et al., 2001), not as a rehearsal strategy used *per se*.

To our knowledge, only one study has investigated the effects of VR on motor learning without simultaneously performing the movements (Hall et al., 1997). Interestingly, this study compared the impact of VR and MI training. Participants were first presented with a series of different patterns of movements, each movement being separated by a period of 15 s. During this 15 s period, depending on group assignment, subjects either (1) imagined the movement twice, (2) repeated a verbal label associated to the movement twice, or (3) imagined the movement once and verbally labeled it once. After the presentation of the movements, subjects performed a puzzle for 10 min, and were then asked to reproduce as many of the movement patterns as they could. The authors found that subjects who had used VR were better than those who had used MI, and that those who employed a combination of the two strategies yielded the best results. Although interesting, the study from Hall and colleagues has several limitations. First, subjects mentally practiced each movement only twice, which is very little in comparison with other studies on mental practice where subjects may mentally rehearse movements for several minutes and across several days (see Schuster et al., 2011). Second, long-term effects of mental practice were not assessed. Finally, the subjects' performance was essentially assessed by calculating the number of movements recalled as well as the accuracy of the correctly recalled movements, thus by measures of motor memory rather than of motor performance (e.g., speed of execution).

Hence, the main objective of the present study was to compare the effects of mental practice with MI or with VR on the speed to perform a sequential motor task derived from the serial reaction time paradigm (Nissen and Bullemer, 1987). By this way, the impact of VR on motor performance was assessed, and this effect could be directly compared with that of MI training. Another objective was to determine whether these two forms of mental practice led to performance gains that were specific to the practiced sequence. Indeed, it has been shown that mental practice with MI of a finger sequence can be beneficial for both trained and untrained sequences (Nyberg et al., 2006; Olsson et al., 2008). If a non-specific effect was found with both MI and VR, this could indirectly suggest that similar processes are involved during these two forms of mental practice. To achieve these goals, we compared the learning and retention of a sequence of lower-limb movements in three groups of healthy subjects: (1) a group who practiced mentally the sequence using MI, (2) a group who practiced mentally the sequence with VR, and (3) a control group who did not engage in any mental practice condition. The specificity of the effects of practice was tested by measuring subject performance in two conditions that differed with regards to the stimuli used: (1) a practiced sequence and (2) a non-practiced sequence. We hypothesized that, compared to the control condition, mental practice using MI and VR would lead to higher levels of improvement on the task, and that this increase in performance would be more important for the practiced sequence.

MATERIALS AND METHODS

SUBJECTS

Thirty healthy right-handed and right-footed subjects ranging in age between 22 and 37 years old (mean = 27.4 ± 4.1 years) were recruited. These participants were assigned to one of three groups: mental practice with MI, MI group ($n = 10$); mental practice with VR, VR group ($n = 10$); and a no mental practice, control group ($n = 10$). All groups were matched with respect to their mean age, years of education, and gender ratio based on analyses of variance and chi-square analyses performed on these variables. The exclusion criteria included major medical problems, neurological disorders, psychological or psychiatric illness, uncorrected hearing impairments, as well as musculoskeletal disorders of the lower limbs. Subjects gave their written consent and were financially compensated for their visits to the laboratory. The study was approved by the ethics committee of the Quebec Institute for Rehabilitation.

MATERIAL

Imaginary distance test

In this test, subjects were asked to imagine walking at a regular pace in a familiar setting using the first-person perspective, and then to judge the distance traveled (see Malouin et al., 2003). They were instructed to imagine walking until the experimenter told them to stop. Unknown to the subjects, each trial was terminated after varying intervals of 15, 25, or 35 s. Administration of these intervals was presented twice and counterbalanced, such that the subjects were not able to predict when to stop walking.

Kinesthetic and visual imagery questionnaire

This questionnaire developed by Malouin et al. (2007) assesses MI vividness. It includes 10 items corresponding to 10 basic movements that subjects must execute then imagine in the first-person perspective. In the first part of the questionnaire (visual subscale) subjects try to "mentally see" the movements when they imagine them; in the second part (kinesthetic subscale) they try to "mentally feel" the movements. After each imagined movement, they rate the clarity of the images/intensity of the sensations that they have formed on a 5-point scale, from 1 (no image/no sensation) to 5 (image as clear as seeing/sensation as intense as during physically performing). Note that in the version of the Kinesthetic and Visual Imagery Questionnaire (KVIQ) used in this study the scale was reversed: five corresponded to no image/no sensation and one to the clearest images/most intense sensations. A score for each subscale was calculated (ranging from 10 to 50) then a total score was computed (ranging from 20 to 100).

Foot-sequence task

The task was performed in an apparatus that consisted of a pedal (13 cm × 35 cm) mounted in a frame (45 cm long, 29 cm wide, and 60 cm high) that was custom made for this research project. The height and length of the pedal could be adjusted to standardize the foot position relative to the ankle axis of rotation, and the foot was secured by two Velcro straps attached to the pedal. A potentiometer fixed on the pedal axis and connected to an electronic relay box could be adjusted to detect three different pedal angles (positions). The relay box was linked to a computer that generated the auditory stimuli and registered the subject response time (ms) and number of errors.

Electromyography

A portable two way electromyography (EMG) device (Pathway MR-20; The Protheus Group) recorded surface EMG activity of two leg muscles, the *tibialis anterior* and the *soleus*, during the different experimental conditions. These EMG recordings served only as a feedback to monitor the absence of muscle contractions during the imagined conditions.

PROCEDURE

The design comprised a total of seven experimental sessions. Session 1 was a pre-training and baseline evaluation, sessions 2–6 were weekly evaluations of subjects' physical and mental performance, while session 7 was conducted several months after session 6 to assess the retention level of the skill. Between sessions 1 through six, subjects in the MI and VR groups mentally practiced a specific sequence of six elements. Subjects in the control group did not practice between sessions, but their performance was nevertheless tested at the same time points as the other two groups.

Testing session 1

After the procedure was fully described to the subjects, participants completed the imaginary distance test as a preparation for MI. Due to time constraints the KVIQ was handed to them to be completed at home and returned in the next session.

Execution of the foot-sequence task. Participants were set up in the apparatus with their left foot attached to the pedal, and were asked to perform the task in a supine position. Note that the left foot was used because performance with this limb was expected to offer more room for improvement than with the right limb. Three foot positions were determined: (1) maximum dorsiflexion (up), (2) middle position, and (3) maximum plantar flexion (down). The relay box was adjusted to recognize these positions. Subjects started the task with their foot in the middle position. They were requested to execute a dorsiflexion in response to a high pitched sound and a plantar flexion in response to a low pitched sound. They were required to move as quickly as possible while making as few errors as possible. After each trial, subjects had to move their foot back to the middle position in order to be ready to move in response to the upcoming target sound. The trials were presented with a fixed inter-stimulus interval of 2000 ms.

Each subject was given 24 practice trials to become familiar with the physical execution of the task. They were then asked to complete trials in two different conditions: sequence A and sequence B. The order of presentation of the two sequences was counterbalanced among groups. In addition, random trials were administered between the two conditions to reduce possible confusion between the two sequences (results for these trials were not included in the analyses). Sequence A corresponded to the following sequence of six foot positions: "up-down-down-up-down-up," while Sequence B consisted of the reverse order: "down-up-up-down-up-down." These sequences were found to be equivalently difficult in a previous pilot experiment (data not shown here). Four blocks were performed with one of the sequences, followed by two blocks of the random trials, and then four blocks of the alternate sequence. Each block consisted of 36 trials (6 sequences of 6 elements), and were separated by 1 min pauses. Before training began, subjects were taught explicitly the series of movements and had to reproduce it *errorless* three times in a row without any auditory cues. The response time (ms) was recorded for each trial.

Imagination of the foot-sequence task. Following assessment of the initial performance on the foot-sequence task, two electrodes were attached to the subject's left leg over the *tibialis anterior* and the *soleus* muscles to record EMG activity during the covert conditions. If such activity was present, subjects were asked to relax, and repeat the imagined block of trials until no significant change in the EMG signals was observed. During testing, subjects in the MI and control groups had to imagine the movements of the sequence, while those in the VR group had to mentally repeat the labels "up" and "down" associated with the sequence. Precisely, during MI, subjects were asked to imagine, as quickly and accurately as possible, four blocks of six sequences for both Sequence A and B, starting with the one they began with during physical execution of the task. MI involved the kinesthetic and visual components of the movements as if subjects were performing the task (first-person perspective). For its part, VR consisted of a silent repetition of the sequence of foot positions (i.e., "up-down-down-up-down-up" and "down-up-up-down-up-down"). After the start signal, subjects with their eyes closed, counted on their fingers the number of sequences they performed mentally, to indicate the exact moment they completed one block (six sequences) of trials. The time, in seconds, taken to imagine each block was recorded with a stopwatch.

Mental practice

Subjects in the MI and VR group were asked to complete 12 practice periods at home before coming to the next testing session. During each practice period, they had to assume a sitting or supine position, and imagine/labeling the sequence without actually moving their foot for 10 separate blocks of trials (10 × 6 sequences = 60 sequences per practice period). Thus, subjects in the MI and VR groups mentally rehearsed 720 times their practiced sequence between each testing session. Subjects were given a logbook in which they were asked to register the time and duration of each training period. Subjects in the control group were not asked to practice the sequences but returned to the laboratory for weekly evaluations.

Testing sessions 2–6

During each testing session, which took place on average 8.4 days (SD = 1.7) apart, subjects had to perform the foot-sequence task both physically and mentally as described previously in the first testing session, except that only two blocks of practice of each sequence (instead of four) were administered. Therefore, all subjects were tested on the foot-sequence task on two blocks of the practiced sequence and two blocks of the non-practiced sequence, separated by two blocks of random trials. Again, subjects in the MI and control groups were asked to perform the task using MI, while subjects in the VR group were required to use covert VR. EMG activity of the *tibialis anterior* and *soleus* muscles was recorded again in session 6 to insure that repeated mental practice did not induce muscular activity. At the end of session 6, subjects were again given the KVIQ to be completed at home in the next few days to determine whether the perception of their imagery ability had changed after several weeks of mental practice.

Testing session 7

All of the subjects who participated in this experiment were later invited to come back to the laboratory for a retention test. Subjects were not previously told about this test to insure that no further practice would occur after training sessions. Twenty-three subjects (MI group, $n = 9$; VR group, $n = 8$; control group, $n = 6$) were re-tested on average 206 (SD = 46) days after session 6. They completed two blocks of the practiced sequence and two blocks of the non-practiced sequence, separated by two blocks of random trials. They also imagined two blocks of each sequence as described previously.

DATA ANALYSIS

Motor imagery ability

The total KVIQ-scores obtained during the first administration of the questionnaire were compared between groups by means of a one-way ANOVA. Further, to determine whether mental practice of a skill during several weeks altered the perception of imagery ability, we compared KVIQ scores at the beginning of the experiment with those obtained after practice by means of a 2 × 3 (Session × Group) ANOVA with repeated measure.

Execution of the foot-sequence task

Only response times were analyzed since subjects made very few errors (mean: 1.6%). First, response times shorter than 100 ms and longer than 2000 ms were discarded. Indeed, it has been shown that genuine reaction times cannot be less than 100 ms (e.g., Luce, 1986) and the cut-off value of 2000 ms was chosen to eliminate trials were subjects erred. Then, response times inferior or superior to two SD of the subject's mean for a given condition were excluded. On this basis, results for one subject from the control group were not included in the analyses because almost 25% of trials were outliers, which strongly suggests that this participant did not fully comply with the instructions. For the other subjects, no more than 8% of the trials were discarded (mean: 2.4%). Response times were compared between groups, for each condition, at baseline (session 1) after 5 weeks of training (session 6), and around 6 months after the end of training (session 7, retention) by means of ANOVAs (See Results).

Imagination of the foot-sequence task

To explore the temporal congruence between executed and imagined movements, we compared the time taken to physically and mentally complete the blocks of sequences. A first descriptive analysis of the data led to an unexpected finding. In fact, individual data showed that some subjects tended to take more time during imagination than during execution of the sequence (over-estimators), some subjects took approximately the same amount of time, while others took less time to imagine the task than to execute it (under-estimators). Moreover, subject tendency to use a given strategy during MI was found to be relatively constant across training. Since the distribution of this unsuspected characteristic was not balanced across groups (e.g., four over-estimators in the MI group, and seven in the control group), comparison between the time taken by subjects to imagine and execute the foot-sequence task was not pursued.

RESULTS

MOTOR IMAGERY ABILITY

Results from the imaginary distance test confirmed that all subjects understood the concept of MI and were able to imagine movements. Indeed, consistent with previous studies (Malouin et al., 2003, 2008), subjects imagined walking farther with increasing time and vice-versa. Also, all subjects succeeded in engaging in MI of the foot-sequence task without significantly contracting their *tibialis anterior* or *soleus* muscles either during the first or sixth session.

As for the KVIQ, the one-way ANOVA performed on the scores obtained during the first administration of the questionnaire showed a significant main effect of Group [$F_{(2,26)} = 6.13$, $p < 0.01$]. Decomposition of this effect revealed that the control group scored significantly lower – thus rated itself as being better at eliciting vivid images and sensations – than both the MI and VR groups ($p < 0.05$). To determine whether mental practice of a skill during several weeks altered the subjects' perception of their imagery ability we compared the KVIQ scores between sessions 1 and 6 by means of a 2 × 3 (Session × Group) ANOVA with repeated measures. The main effect of Session, as well as the Group × Session interaction failed to reach the level of significance, suggesting that subjects, on average, did not change their rating of their own MI ability over time.

EXECUTION OF THE FOOT-SEQUENCE TASK

Six subjects (one in the MI group, two in the VR group, and three in the control group) did not attend the retention session for different reasons (could not be contacted, refused to come back). **Figure 1** provides an overview of the evolution of the mean response times for the practiced and non-practiced

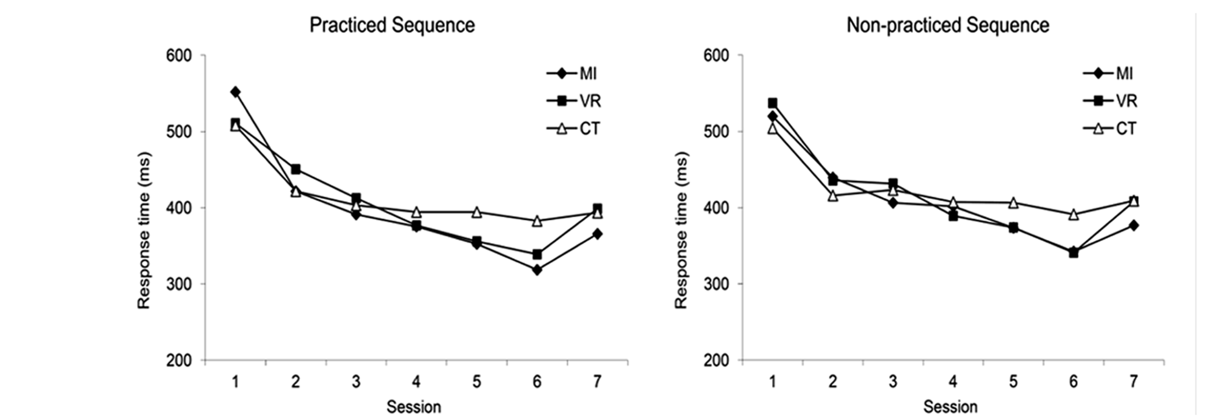

FIGURE 1 | Mean response times for the practiced and non-practiced sequence, in each group, across the seven sessions.

sequence, in each group, across the seven sessions. Response times for both conditions decreased in all groups between sessions 1 and 6, and this decrease was more important in the MI and VR groups compared to the control group. Also, while response times remained relatively stable between sessions 6 and 7 in the control group, they increased in the MI and VR groups. In the following sections, we provide statistical analyses of these data. The performance change between sessions 1 and 6 were analyzed separately ($n = 29$) from the performance change between sessions 6 and 7 ($n = 23$).

Training: performance change between sessions 1 and 6

First, a one-way ANOVA conducted on responses times at session 1 showed that the performance levels before training did not differ significantly between groups [$F_{(2,26)} = 0.51$, $p = 0.608$]. Thus, possible differences between groups after practice should reflect the effects of the different training regimen. **Figure 2** shows mean responses times for the practiced and non-practiced sequence, in each group, at sessions 1 and 6. Results of a 3 × 2 × 2 (Group × Condition × Session) ANOVA performed on the response times showed a significant main effect of Session [$F_{(1,26)} = 150.51$, $p < 0.001$, $\eta_p^2 = 0.85$] as well as a significant Group × Session interaction [$F_{(2,26)} = 3.40$, $p < 0.05$, $\eta_p^2 = 0.21$], indicating that the three groups improved their performance after training, but that this change in performance differed among groups. Subsequent paired t-tests with a Sidak correction conducted within each group showed that response times for both sequences significantly decreased between session 1 and 6 in the three groups ($p < 0.001$). To further characterize the Group × Session interaction, we thus conducted three separate 2 × 2 (Group × Session) ANOVAs on data of the groups taken two by two (MI vs. control, VR vs. control, and MI vs. VR). Results showed that the interaction between Group and Session was significant when the MI group was compared to the control group [$F_{(1,17)} = 7.00$, $p < 0.05$, $\eta_p^2 = 0.29$], approached significance between the VR and control groups [$F_{(1,17)} = 7.00$, $p = 0.067$, $\eta_p^2 = 0.18$], but was not significant between the MI and VR groups. Note that in the 3 × 2 × 2 (Group × Condition × Session) ANOVA, neither the effect of Condition, nor any other interaction involving the effect of Condition reached statistical

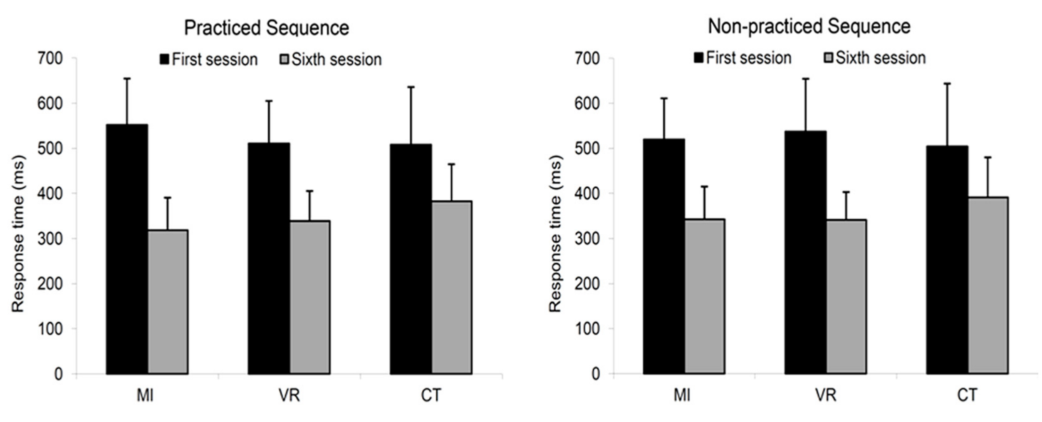

FIGURE 2 | Mean (+SD) responses times for the practiced and non-practiced sequence, in each group, at sessions 1 and 6. MI, Motor imagery group; VR, verbal rehearsal group; CT, control group.

significance, suggesting that the changes in response times were not statistically different between the practiced and non-practiced sequence.

Retention: performance change between sessions 6 and 7

Figure 3 shows mean responses times for the practiced and non-practiced sequence, in each group, at sessions 6 and 7. The results of a 3 × 2 × 2 (Group × Condition × Session) ANOVA performed on the response times showed a significant main effect of Session [$F_{(1,20)} = 32.42$, $p < 0.001$, $\eta^2_p = 0.62$] as well as a significant Group × Session interaction [$F_{(2,20)} = 8.06$, $p < 0.01$, $\eta^2_p = 0.45$], indicating that there was a change in performance after several months without practice but that this change differed between groups. In fact, paired *t*-tests with a Sidak correction conducted within each group revealed that response times for both sequences significantly increased ($p < 0.001$) in the MI and VR groups but did not change in the control group (but remember that the control group had not improved as much as the other groups in the training phase). This result showed that the additional gain in performance obtained after training in the two mental practice groups compared to the control group did not last after several months without practice. To further investigate whether the change in response time differed between the MI and VR groups, we performed a 2 × 2 (Group × Session) ANOVA on the data of these two groups. This analysis did not show any significant interaction between Group and Session, indicating that the decrease in performance between sessions 6 and 7 was equivalent for the MI and VR groups. Finally, note that in the 3 × 2 × 2 (Group × Condition × Session) ANOVA, no interaction involving the effect of Condition reached statistical significance, showing that the changes in response times were equivalent between the practiced and non-practiced sequence.

DISCUSSION

The main results of this study showed that, compared with no mental training, both mental practice with MI and with VR enhanced performance of a sequential motor skill after a few weeks of training. Furthermore, the two conditions of mental practice led to improved performance of the trained sequence as well as an untrained sequence, suggesting a non specific effect of training. After several months without mental practice however, performance returned to similar levels in the mental training groups and the control group, indicating that the gain provided by mental practice after 5 weeks of training was not maintained over time.

EFFECTS OF MENTAL PRACTICE ON MOTOR LEARNING

Mental practice with motor imagery

When considering the effects of mental practice with MI, our findings are consistent with a large body of research in sport settings, which support the use of MI training to improve the learning of sequential skills (see Feltz and Landers, 1983; Driskell et al., 1994). As shown by other studies, it is also possible to improve motor sequence skills with mental practice based on MI even without the extrinsic motivation of competitive athletic performance (Pascual-Leone et al., 1995; Jackson et al., 2003; Gentili et al., 2006; Nyberg et al., 2006; Olsson et al., 2008; Debarnot et al., 2009; Debarnot et al., 2011). For example, by using the same task as the one of the present study, Jackson et al. (2003) showed that five training periods of mental practice with MI over 1 week led to a significant improvement in performance in healthy young subjects. For their parts, Olsson et al. (2008) showed that a combination of physical and mental practice of a finger tapping sequence over 6 weeks tended to induce greater improvement in the speed of execution of the sequence than physical practice alone. In the present study, subjects in the MI group combined physical and mental practice since they executed the sequence at each testing session. Our results are thus directly in line with those of Olsson and colleagues and extend them to the learning of a sequence involving the lower limb.

Such improvements in performance after mental practice have been linked with changes in the cortical maps associated with the movements performed (e.g., Pascual-Leone et al., 1995; Jackson

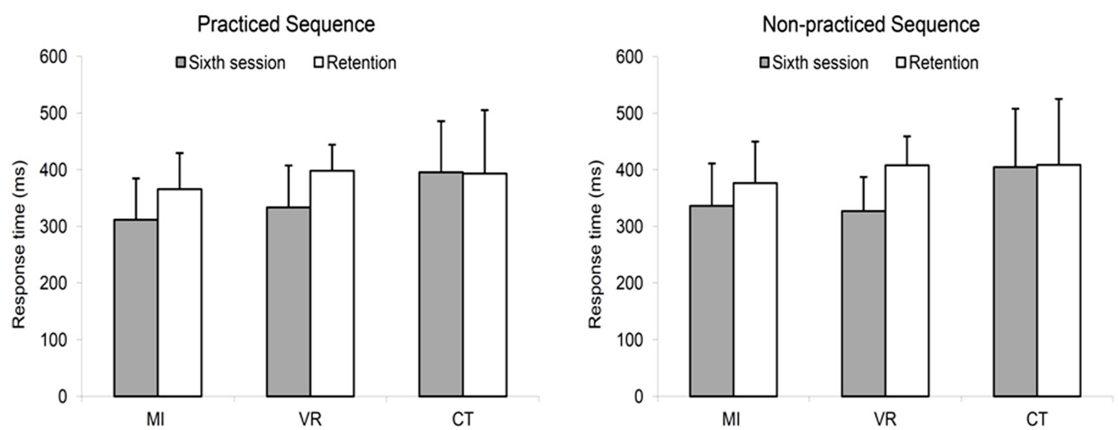

FIGURE 3 | Mean (+SD) responses times for the practiced and non-practiced sequence, in each group, at sessions 6 and 7 (Retention). MI, Motor imagery group; VR, verbal rehearsal group; CT, control group.

et al., 2003; Debarnot et al., 2011). For example, in the study by Jackson et al. (2003) mentioned above, the authors showed that the performance improvement after mental practice was accompanied by an increase in activity in the orbitofrontal cortex as well as a decrease in activity in the cerebellum, both changes in the functional representation of the skill that had previously been shown to occur after physical practice of the same task (Lafleur et al., 2002). Hence, mental practice with MI of sequential skills can access and modify the motor representation of the practiced skills, just like physical practice.

Mental practice with verbal rehearsal

It is of interest that our results also show improvements in performance after VR that were similar to those obtained with MI training. VR as a technique to improve motor skills has been considerably less studied than MI training, even in athlete populations. Furthermore, although the impact of VR training has generally been shown to be positive, it was essentially in a context where subjects labeled key elements (via self-talk) of a given movement concomitantly to its actual execution (e.g., Ziegler, 1987; Ming and Martin, 1996; Landin and Hebert, 1999; Zinnser et al., 2006). To our knowledge, the only published study that specifically explored the impact of VR as a training technique decoupled from actual execution was that of Hall et al. (1997) where the effects of mental practice with VR and MI on the memorization of different movements were compared. However, as reported in the introduction, the study of Hall and colleagues had important limitations and notably the fact that subjects mentally practiced the movements only twice and that the main outcome was a measure of recall. Our results thus add an original contribution to the literature on mental training as they show that the increase in speed – a real measure of motor performance – in a sequential motor task was similar after a substantial amount of VR and after the same amount of MI training. Note however that the present results do not allow us to conclude that VR (combined with physical practice) is truly more efficient than physical practice alone since the difference in the performance improvement between the VR and control groups only approached significance (whereas this difference was significant between the MI and control groups). The impact of VR on motor performance needs thus to be further investigated.

Still, one possible explanation of the effect of VR comes from the links between language and movements, as for example proposed in the action-language-imagination model by Annett (1996). According to this model, there are two main channels to acquire information about a skill: a motor channel and a verbal channel. Between the two channels is the action-language bridge which makes it possible to verbally describe an action but also to generate an action on verbal instructions. Assuming the existence of such a close relationship between language and movements, it is thus conceivable that by rehearsing the different foot positions, subjects implicitly evoked part of the action itself, thereby engaging motor representations involved in motor sequence learning. More recently, embodied theories of language have put forward the notion that brain areas involved in perception and action are also implicated in the representation and processing of language (e.g., Pulvermuller and Fadiga, 2010). In particular, neuroimaging studies have shown that the processing of action-related language – such as action words – recruits sensorimotor brain areas similar to those that would be activated during actual execution of the actions described by the words (e.g., van Dam et al., 2010; Hauk and Pulvermuller, 2011).

In the present study the words "up" and "down," although they were not action verbs, clearly referred to an action. It is thus possible that motor representations of the movements were implicitly evoked when subjects mentally rehearsed these words. However, this remains speculative. In future studies, it would be interesting to directly test whether MI of a given action and the processing of key words associated with this action would activate similar brain regions. Furthermore, brain plasticity associated with both VR and MI training should be explored.

NON-SPECIFIC LEARNING EFFECT

An interesting finding of this study is that the level of improvement was similar for the practiced and the non-practiced sequence, after both MI and VR training. Nyberg et al. (2006) assessed performance of two finger-tapping sequences before and after 1 week of training in two groups of subjects. During training, all subjects practiced one of the two sequences for four sessions spread over 1 week. Half of the participants performed physical practice while the other half performed mental practice based on MI. A positive effect of training (either physical or mental) was shown for both the trained and untrained sequence, although the gain in performance was significantly larger for the trained sequence. In a subsequent study, by using the same finger-thumb opposition task, Olsson et al. (2008) showed that a combination of physical and mental practice for 6 weeks induced a significant increase in tapping performance for the trained sequence, but also, to a lesser extent, for an untrained sequence. Thus, the present results are in line with these findings and extend them, since they show that the trained and an untrained sequence may equally benefit from mental practice.

It has been shown that the learning of the abstract structure of a sequence (i.e., the relationship between repeating elements) can be generalized to an isomorphic sequence (Dominey et al., 1998). For example, the sequences ABCABC and DEFDEF share the same format as they follow the rule 123123 (Dominey et al., 1998). Considering that the two six-element sequences used in the present experiment shared the same abstract structure (i.e., 122121), part of the non-specific learning observed might be due to the acquisition of that structure, an acquisition that could have helped the anticipation of the subsequent element of the sequence even in the untrained sequence. Also, as the learning of a sequence develops, its coding in motor coordinates develops (Hikosaka et al., 2002), thus reducing the speed to perform each movement of the sequence. The "strengthening" of the specific motor representation for the dorsiflexion and the plantar flexion during mental practice of the specific sequence could thus have been transferred to the non-specific sequence since both sequences were composed of the same two movements.

Finally, it is also very interesting that mental practice based on MI and on VR induced a similar non-specific effect. This latter result suggests that similar processes are potentially engaged during MI training and VR.

RETENTION AFTER SEVERAL MONTHS WITHOUT PRACTICE

Another novel finding of this study is that there was a similar decrease in performance in the MI and VR groups after about 6 months without practice, whereas no significant decrease was observed in the control group (who had improved less than the other groups during training). Hence, the level of performance in the three groups was equivalent at the retention session. This suggests that physical practice was the key element for long-term retention of this sequential motor task, and that MI and VR offered a boost in performance that was present during training only. To our knowledge, this is the first time that mental practice effects were assessed at such a long-term follow up. Most of the studies on mental practice with MI, either in Sport, Psychology, or Medicine, have investigated learning effects of MI training, with simple pre-training/post-training designs (see Schuster et al., 2011). Hence, this result raises a potentially important limit of mental practice, at least for a sequential motor task that must be performed at maximum speed. Further studies should explore long-term effects of mental practice on different parameters of motor performance, such as accuracy or strength. Finally the fact that the decrease in performance at retention was similar in the MI and VR groups once again suggests that similar processes could be involved in both forms of mental practice.

MOTOR IMAGERY

Beyond the investigation of the impact of mental practice, our results also add to the literature on psychophysical studies of MI. Several chronometric studies have shown that the time taken to imagine a movement is similar to that taken to execute the same movement (Decety et al., 1989; Sirigu et al., 1995; Papaxanthis et al., 2002; see Guillot and Collet, 2005). However, while this might be true at the level of group analysis, comparison of individual data from the actual and imagined sequences in the present study showed that each subject had his or her own strategy for imagining movements, and that this strategy remained fairly constant from one session to the next. Indeed, we found that, on an individual basis, subjects often under-estimated or over-estimated the time it took to actually complete the sequences during MI of the task. In addition, subjects remained either under-estimators or over-estimators even after extensive MI training. This suggests that the temporal congruence between imagined and executed performance is related to individual differences and that it does not only reflect the level of MI ability *per se*. Finally, the lack of significant changes in the KVIQ scores after extensive MI training also supports the notion that some characteristics of subjects' MI ability (in this case their subjective rating of MI vividness) are relatively stable, at least over a few weeks.

LIMITS

At least two limitations of this study should be acknowledged. First, the number of subjects included was relatively small. In particular, the fact that seven subjects did not attend the retention session leads us to interpret the retention results with some caution. Second, mental practice was performed at home and although subjects reported to comply with the instructions not to move during practice, EMG activity was not controlled during the training sessions. It is thus possible that some subjects may have not totally inhibited their movements during MI training. Note however, that subjects imagined the sequence without any EMG activity at sessions 1 and 6.

CONCLUSION

Taken together, the results of the present experiment show that mental practice based on MI and on VR improved the speed to perform a sequential motor task and that this improvement was similar between the MI and VR groups. Although further research is needed to confirm the impact of VR on motor performance, the present results thus suggest that VR could be a useful alternative to MI when using mental practice. It is now well established in the literature that the use of mental practice with MI can provide an adjunct to traditional physical therapy in a rehabilitation setting where specific series of movements often need to be learned or re-learned (see Dickstein and Deutsch, 2007; Malouin and Richards, 2010; Malouin et al., 2013). However, some neurological patients could encounter more difficulties to imagine movements (which is a cognitively demanding activity) than labeling them. The use of VR instead of MI during mental practice – at least in the first stages of mental training – with these patients could thus be of particular interest; this remains to be tested.

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The effects of mental practice in neurological rehabilitation; a systematic review and meta-analysis

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Objective: To investigate the beneficial and adverse effects of a mental practice intervention on activities, cognition, and emotion in patients after stroke, patients with Parkinson's disease or multiple sclerosis.

Methods: Electronic databases PubMed/Medline, PEDro, Science Direct, Cochrane Library, PsycINFO, Rehadat, Embase, and Picarta were searched until June 2012. Fourteen randomized controlled trials in stroke and two randomized controlled trials in Parkinson's disease were included, representing 491 patients (421 with stroke). No randomized controlled trials in multiple sclerosis were identified. The methodologic quality of the included trials was assessed with the Amsterdam-Maastricht-Consensus-List (AMCL). Information on study characteristics and outcomes was summarized and evidence for effects described. Data from individual studies in stroke with same outcome measures were pooled.

Results: The included 16 randomized controlled trials were heterogeneous and methodologic quality varied. Ten trials reported significant effects in favor of mental practice in patients with stroke ($n = 9$) and Parkinson's disease ($n = 1$). In six studies mental practice had similar effects as therapy as usual ($n = 5$ in stroke and $n = 1$ in Parkinson's disease). Of six performed meta-analyses with identical measures in stroke studies only two showed significant effects of mental practice: short-term improvement of arm-hand-ability (ARAT: *SMD* 0.62; 95% *CI:* 0.05 *to* 1.19) and improvement of performance of activities (NRS: *SMD* 0.9*;* 95% *CI:* 0.04 *to* 1.77). Five studies found effects on cognition (e.g., effects on attention, plan actions in unfamiliar surroundings) and four reported observed side-effects, both positive (e.g., might increase motivation and arousal and reduce depression) and negative (e.g., diminished concentration, irritation).

Conclusions: Mental practice might have positive effects on performance of activities in patients with neurological diseases, but this review reports less positive results than earlier published ones. Strengths and limitations of past studies are pointed out. Methodologic recommendations for future studies are given.

Keywords: neurorehabilitation, mental practice, systematic review, meta-analysis

INTRODUCTION

Neurological pathologies affect many patients profoundly, causing loss of activities, which often leads to intensive rehabilitation periods (Munneke et al., 2010; Keus et al., 2012). Three often researched neurological conditions of the upper motor neuron are stroke, Parkinson's disease, and multiple sclerosis. The complexity and intensity of neurological multidisciplinary rehabilitation leads to high costs, which will increase as the numbers of patients with a neurological disorder rise (Evers et al., 2004; Struijs et al., 2005; Findley, 2007).

While it is reasonably established that the overall process of neurological rehabilitation is effective, there is little evidence to support many specific rehabilitation therapeutic techniques (Keus et al., 2007a; Langhorne et al., 2009). Currently task orientated practice (i.e., practising a meaningful activity within the context of relevance) and intensity are considered the basis for effective therapeutic techniques (Trombly and Wu, 1999; Langhorne et al., 2009).

Mental practice of tasks is a relatively new therapy that is receiving a lot of attention within rehabilitation research (de Vries and Mulder, 2007; Langhorne et al., 2009). Mental practice can be defined as: "*The repetition or rehearsing of imagined motor acts with the intention of improving their physical execution*" (Malouin and Richards, 2010). Practicing a skill mentally is a potential method to increase the amount of practice during rehabilitation in a safe way with relatively low costs. After initial learning, the mental practice technique can be practiced by the patient independent from the therapist, location, and time of the day.

Over the last decade, many articles investigating the effects of mental practice have been published, including five systematic reviews (Braun et al., 2006; Zimmermann-Schlatter et al., 2008; Nilsen et al., 2010; Barclay-Goddard et al., 2011; Cha et al., 2012). Within neurological rehabilitation, the reviews are restricted to evidence of mental practice in stroke populations. Four reviews focused on upper limb abilities (Zimmermann-Schlatter et al., 2008; Nilsen et al., 2010; Barclay-Goddard et al., 2011; Cha et al., 2012). All reviews included a relatively small number of randomized or clinically controlled trials [four (Zimmermann-Schlatter et al., 2008), five (Braun et al., 2006; Cha et al., 2012), or six (Nilsen et al., 2010; Barclay-Goddard et al., 2011) trials]. The total number of participants on which the evidence was based within the separate reviews ranged from 86 (Zimmermann-Schlatter et al., 2008) to 146 (Cha et al., 2012). All systematic reviews conclude that mental practice might be a potential tool to improve motor functions and activities, but that no definite conclusions on the effects of mental practice can be drawn yet, because the evidence base is relatively small. In addition, the reviews recommend that future research should include identification of who will probably benefit most from mental practice, incorporate follow up measuring points (retention) and investigate whether there are differences in effects of the kind of imagery used (e.g., kinesthetic vs. visual imagery and first vs. third person's view).

Despite the number of recent reviews, there is a need for constant updates of evidence because of the increasing numbers of publications and developments made in this specific area of expertise. Barclay-Goddard et al. (2011) described on-going trials in their Cochrane review in 2011 and estimated that with those studies included the population size on which the evidence would be based would triple (well over 400 participants included). Indeed new studies including some with relatively large sample sizes have been published recently (Ietswaart et al., 2011; Welfringer et al., 2011; Braun et al., 2012; Schuster et al., 2012) and have not yet been included in a review.

Studies assessing the potential of mental practice up until now focused mainly on physical effects. Nilsen et al. (2010) concluded in their review that the variety of effects should be reported more extensively and investigated in future research and Barclay-Goddard et al. emphasize that side-effects, compliance, and integrity should be monitored more closely and reported in future studies (Barclay-Goddard et al., 2011). Mental practice has been shown to regulate arousal, increase control of emotions and improve self-awareness and self-confidence in athletes (Murphy and Jowdy, 1992; Martin et al., 1999) and increase quality of life in patients with breast-cancer (Freeman et al., 2008). At the same time mental imagery may lead to negative side-effects in some patients with complex regional pain syndrome: pain and swelling increased after mental practice use (Moseley et al., 2008).

Although the evidence is yet inconclusive mental practice is recommended to improve arm-hand-abilities in stroke guidelines (Royal College of Physicians of London, 2008; Australian Stroke Foundation, 2010).

Besides in stroke, mental practice has been used in patients with Parkinson's disease and multiple sclerosis. Although it is not possible to compare these target populations in terms of pathology, symptoms, and recovery pattern, the clinical approach for all three patient groups share considerable similarities (e.g., the mental practice instructions given in clinical practice). Within rehabilitation all groups need intensive, task relevant practice. The underlying hypothesis for the value of mental practice is the same: (1) activation of brain regions related to motor function (Johnson, 2000; Cunnington et al., 2001) and (2) increase of intensity of practice without the need to take issues related to safety and physical fatigue into account (Keus et al., 2007b; van Peppen et al., 2007).

The effects of mental practice in Parkinson's disease and multiple sclerosis have not been taken into account in earlier reviews.

The main objective of this study was *to undertake a systematic review and a meta-analysis of randomized controlled trials investigating the beneficial and adverse effects of a mental practice intervention on activities, cognition, and emotion in patients after stroke, patients with Parkinson's disease or patients with multiple sclerosis.*

Strengths and limitations of past studies will be pointed out in order to give recommendations in the discussion section on the content and organization of future trials (Craig et al., 2008).

METHODS

An overview of the search strategy, selection criteria, quality assessment, and meta-analysis is given in **Figure 1**.

DATA SOURCES

Computer-aided search was performed by four researchers (Susy Braun, Melanie Kleynen, Tessa van Heel, Nena Kruithof) using PubMed/Medline, PEDro, Science Direct, Cochrane Library, PsycINFO, Rehadat, Embase, and Picarta. The authors hand-searched reference lists of obtained articles (reference and author tracking). Key words used were: *stroke, Parkinson's disease, multiple sclerosis, mental practice, movement and motor imagery, motor learning, rehabilitation, physical therapy, occupational therapy, activities of daily living*. These search terms were used in Dutch and German articles as well and were translated if necessary. The detailed search strategy is available from the authors.

STUDY SELECTION

Type of study

The studies selected in the review were all available randomized controlled trials in English, German, and Dutch up to June 2012 that reported the effects of mental practice on the improvement of activities during the rehabilitation of adult participants after stroke, with Parkinson's disease or multiple sclerosis. In cross-over trials, only the first phase of the study was taken into account. A study with mixed population was only selected if the majority (over 50%) of participants had been diagnosed with stroke, Parkinson's disease, or multiple sclerosis.

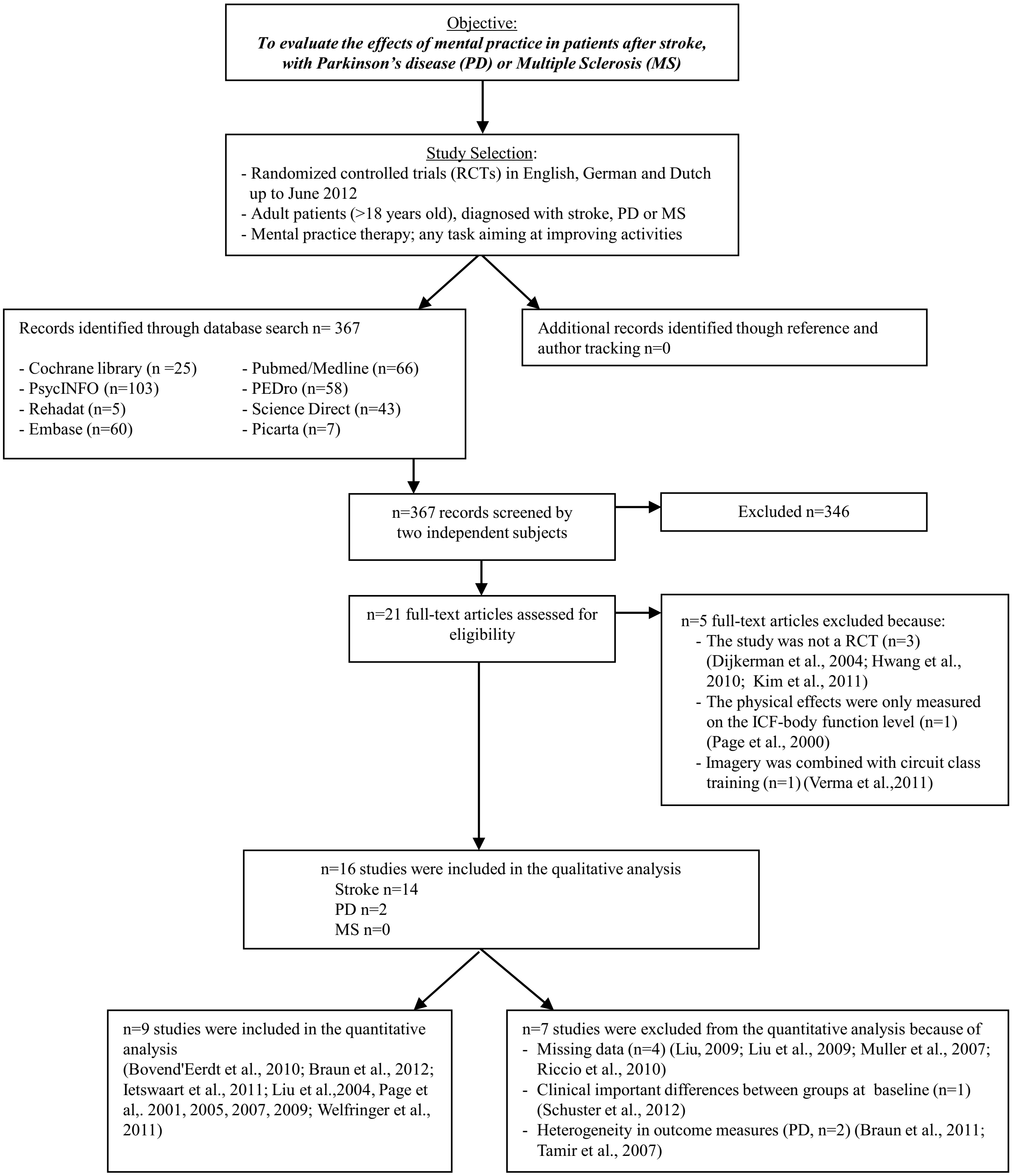

FIGURE 1 | Overview of literature search. Abbreviations: MP, mental practice; PD, Parkinson's disease; MS, multiple sclerosis; RCTs, randomized controlled trials.

Type of intervention

The mental practice intervention could be added to therapy (e.g., using a taped instruction), embedded in therapy (e.g., problem-solving strategies in which overt movements are combined with mental practice during physical or occupational therapy) or given as an independent intervention. Studies in which special equipment was required (such as electro-myographic stimulation and feedback or forms of virtual reality with computer simulation) were excluded. The content of the control intervention should allow the assessment of possible effects of a mental practice intervention.

Type of outcome

Outcome measures can be divided into categories according to the international classification of the World Health Organization (ICF; WHO, 2013) of "function" (e.g., a function could be "pain" measured with a "numeric rating scale"), "activity" (e.g., an activity could be "standing up from a chair" measured with a "timed up and go") and "participation" (e.g., participation could be "providing meals" or "performing (paid) work"). For patients it is important that interventions reduce activity limitations to enable participation in society after returning home. Randomized controlled trials were selected if at least one measure was used for assessing physical effects on the activity level.

DATA EXTRACTION AND QUALITY ASSESSMENT

Screening on tittle and abstract was performed by two researchers (Susy Braun, Melanie Kleynen) independently. If based on the information in the abstract, it was not clear whether the study should be included the full-text of the article was assessed.

Methodologic quality assessment of the studies was assessed using the Amsterdam-Maastricht Consensus List for Quality Assessment (AMCL; Van Tulder et al., 2003). The AMCL was originally developed by van Tulder et al. for the Cochrane Collaboration Back Group and includes all criteria of other prominent quality scales like the Delphi List (Verhagen et al., 1998). It rates a study's internal validity and statistical reporting using an 11-point scale (12 criteria), with higher scores indicating higher quality. Each criterion was scored either positive (+, 1 point), negative (−, 0 points), or unclear (?, 0 points), leading to a maximum score of 11 points per study (1 point for the items 2–11; ½ point for the items 1a and 1b).

To increase uniformity in the assessment the validity criteria were defined and then discussed by the two researchers (Susy Braun, Melanie Kleynen). Each item of the AMCL was explained in a separate document that provided uniform operationalization of criteria. In the Appendix the definitions and cut-offs of the criteria of the AMCL are described (**Table A1**). For example "an acceptable percentage of withdrawals" (criterion 7) was defined as: 10% during the intervention period and from the remaining sample 10% during follow-up as suggested by Van Tulder et al. (2003) Compliance (criterion 5) was considered acceptable if participants themselves or therapists and relatives reported that the participants followed the given instructions. A follow-up period (criterion 10) of at least 3 months was considered clinically relevant for this type of intervention. For these last two mentioned criteria (criteria 5 and 10) reviews of other interventions within health care were used as standard, for generally accepted references in literature were not found (Huibers et al., 2003; Van Tulder et al., 2003). If disagreement on the scores persisted, a third researcher (Anna Beurskens) was approached to reach consensus. A study was defined as being of "sufficient quality" if the score was equal to or above six points. As standard references from the literature are missing, the cut-off was defined by the authors after references from other reviews in physical therapy were taken into account (van Tulder et al., 2001; Van Tulder et al., 2003; Huibers et al., 2003).

Authors of the included articles were contacted to clarify the items on which a question mark was scored. Both scores (blinded assessment as well as after contact with authors) are presented.

Information was extracted from each included trial on: (1) study and population (including number of participants and mean age); (2) type of intervention. We for instance wanted to know if an instruction period for therapists and participants was embedded within the mental practice intervention period (e.g., stepwise approach, tools to check compliance) and what the content of the mental imagery session would be (e.g., what activities were rehearsed and how the imagery was instructed e.g., tape, therapist.); (3) type of outcome measure for physical recovery (primary and secondary measurements, assessment time points, and follow-up period); (4) conclusion (is mental practice recommended and what are the (significant) effects on physical recovery). The conclusions were based on the results and conclusions in the articles but summarized by the independent researchers; (5) All included articles were screened on possibly reported effects on cognition or emotion as well as side-effects (quantitative and qualitative measures). If (secondary) measures were used to consciously search and systematically identify effects on cognition or emotion within the study design the results were categorized as "effects." Side-effects are described as effects that were not intended, but were observed and reported. These side-effects could be therapeutic (positive) or adverse (negative). Both independent reviewers extracted data from the full papers by using a pre-structured standard form.

DATA SYNTHESIS OF THE META-ANALYSIS

A meta-analysis was conducted using Review Manager version 5.1.6. (The Nordic Cochrane Centre TCC, 2011). Post intervention scores and if possible follow-up scores (at least 3 months) were used. Short- and long-term effects of the intervention were distinguished for two reasons: initial effects might extinguish over time and most studies did not perform a follow-up. Data from both measuring moments were analysed separately. Studies were excluded from the analyses if not all necessary data was provided in the article. No data was imputed.

If a study included two control groups, mental practice was compared to the group with the least chance of improvement (e.g., control group). If no significant differences were found between those groups, it was assumed that no differences would be found between the two experimental groups.

Studies with identical physical effect measurement instruments or studies with instruments measuring the same construct were pooled. The Mean Difference (MD) and 95% confidence interval (95% CI) was used if data was based on identical measurement instruments and the Standardized Mean Difference (SMD) for data based on different measurement instrument. Statistical heterogeneity was assessed using the I^2-statistic. If I^2 was greater than 50% outcomes were pooled using SMD with a random effects model. If there was a big variance in Standard Deviations (SD) across studies, reflecting differences in the real variability of outcomes, we also used the SMD. Sensitivity analysis was done to investigate the influence of studies with ACML scores below 6 (lower quality studies). If for instance data were pooled from studies with both lower and high quality, the analysis was performed first with all studies and then repeated without the lower quality studies (Barclay-Goddard et al., 2011).

RESULTS

In total 367 articles were identified in Pubmed/Medline ($n = 66$), PEDro ($n = 58$), Science Direct ($n = 43$), Cochrane Library ($n = 25$), PsychINFO ($n = 103$), Rehadat ($n = 5$), Embase ($n = 60$), and Picarta ($n = 7$) and 346 were rejected based on title and abstract due to the following reasons: (1) the study was not a randomized controlled trial; (2) the study population did not meet the inclusion criteria; (3) the use of mental practice considered specific equipment; (4) physical effects were only measured on the ICF-body function level; (5) a combination of the reasons above. Of the 21 remaining studies another five articles were excluded after reading the document full-text: one of the studies investigated the effects of mental practice only on the ICF-body function level (only the Fugl Meyer Assessment was used as outcome measure; Page, 2000), three studies were not a randomized controlled trial (Dijkerman et al., 2004; Hwang et al., 2010; Kim et al., 2011), and the last article which was excluded compared imagery combined with circuit class training with Bobath. As the control study did not involve circuit class training, it was unclear what the surplus of the imagery training would be (Verma et al., 2011). Furthermore, the effectiveness and efficiency of circuit training has been established in earlier research (van de Port et al., 2012).

No new articles were retrieved by using reference- and author tracking, leading to a total of sixteen included studies of which 14 in stroke patients and two in patients with Parkinson's disease. No randomized controlled trials with patients with multiple sclerosis were found. In total, 491 participants were included in this systematic review; 421 participants after stroke and 70 participants with Parkinson's disease. The total number of participants in a single study varied from 10 (Page, 2000) to 121 participants (Ietswaart et al., 2011). Group sizes for the experimental intervention varied from 5 to 39 and for the control intervention from 5 to 32 (Page et al., 2009; Ietswaart et al., 2011).

EFFECTS PHYSICAL OUTCOME AND METHODOLOGIC QUALITY

The scores on the AMCL (range 0–11 points) of the included studies varied from 3.5 to 8 points after blinded assessment of the reviewers. After additional information was retrieved through authors contact (directly or through earlier confirmed information by the authors in the Cochrane review (Barclay-Goddard et al., 2011)) to clarify the questions marks the scores ranged from 6 to 9 points (**Table 1**).

Based on the scores after assessment of the articles by the independent reviewers of the text only, 11 of the 16 studies scored 6 points or more and were considered to have sufficient methodologic quality (Page et al., 2001, 2005, 2009; Liu et al., 2004; Tamir et al., 2007; Liu, 2009; Bovend'Eerdt et al., 2010; Braun et al., 2011a, 2012; Ietswaart et al., 2011; Welfringer et al., 2011). After additional information was processed three more studies came to a total score above six points (Page et al., 2007; Riccio et al., 2010; Schuster et al., 2012). Of these 14 studies with at least sufficient quality, half ($n = 7$) showed overall positive effects of mental practice on arm-hand-function, activities of daily living and mobility of which six in stroke (Page et al., 2001, 2005, 2007, 2009; Liu et al., 2004; Riccio et al., 2010) and one in Parkinson's disease (Tamir et al., 2007). In three high quality studies in stroke positive results were found in favor of the experimental group but not on all outcome measures (Liu, 2009; Welfringer et al., 2011; Schuster et al., 2012) and four high quality studies reported similar effects in the control and experimental group, of which three in stroke (Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Braun et al., 2012) and one in Parkinson's disease (Braun et al., 2011a). Of the two remaining low quality studies in stroke, one study did not find significant differences between groups (Muller et al., 2007) and one study had mixed results (Liu et al., 2009).

EFFECTS ON PHYSICAL OUTCOMES IN RELATION TO PATIENT CHARACTERISTICS

Study characteristics of the included randomized controlled trials are shown in **Table 2**.

Age of the participants varied from 40 to 84 years. The time post-stroke differed greatly, ranging from 0 to 7 days after stroke (Liu et al., 2009) to the chronic phase of recovery (>6 months after stroke; Page et al., 2007; Schuster et al., 2012). The average time after the diagnosis of participants with Parkinson's disease was between 5.2 and 7.8 years. Based on these qualitative descriptions mental practice seems to have potential effects in all ages of participants and phases of stroke recovery. In participants with Parkinson's disease, effects of mental practice were more often reported in the two included studies in participants with Hoehn and Yahr stage 1 or 2.

EFFECTS ON PHYSICAL OUTCOMES IN RELATION TO INTERVENTION CHARACTERISTICS

Six studies embedded mental practice in therapy (Liu et al., 2004, 2009; Tamir et al., 2007; Bovend'Eerdt et al., 2010; Braun et al., 2011a, 2012), nine studies added mental practice to therapy (Page et al., 2001, 2005, 2007, 2009; Muller et al., 2007; Liu, 2009; Riccio et al., 2010; Ietswaart et al., 2011; Welfringer et al., 2011) and one study investigated both embedded and added mental practice (Schuster et al., 2012).

The intervention in the control group varied from a single intervention like relaxation therapy (Page et al., 2005, 2007), (general) information (Page et al., 2001), embedded therapy as usual (Muller et al., 2007; Tamir et al., 2007; Page et al., 2009; Bovend'Eerdt et al., 2010; Riccio et al., 2010; Braun et al., 2011a, 2012; Ietswaart et al., 2011; Welfringer et al., 2011; Schuster et al., 2012) to therapy according to the demonstration-then-practice method (Liu, 2009; Liu et al., 2004, 2009).

The activities or skills practiced in the intervention group could be restricted to only movements of the arm (e.g., drinking from a cup; Page et al., 2005) or could contain complex tasks involving the entire body (e.g., going to the park; Liu et al., 2009). Frequency of the intervention varied from two to five times a week, while the intervention lasted between 30 and 60 min per session and continued for 2 to 10 weeks. The included studies used different types of imaging (Mulder, 2007): participants were offered kinesthetic motor imagery (Page et al., 2005; Riccio et al., 2010; Ietswaart et al., 2011; Welfringer et al., 2011), or a combination of kinesthetic and visual motor imagery (Page et al., 2001, 2007, 2009; Liu et al., 2004, 2009; Muller et al., 2007; Tamir

Table 1 | Quality assessment of internal validity of the RCTs with the AMCL: stroke and Parkinson's disease (PD) population.

Criterion	Page et al., 2001	Liu et al., 2004	Page et al., 2005	Page et al., 2007	Muller et al., 2007	Liu et al., 2009	Liu, 2009	Page et al., 2009	Riccio et al., 2010	Bovend'Eerdt et al., 2010	Ietswaart et al., 2011	Welfringer et al., 2011	Braun et al., 2012	Schuster et al., 2012	Tamir et al., 2007	Braun et al., 2011a
(1A) Randomization	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
(1B) Concealment of allocation	+	+	+	?	– (?)	+	+	+	+	+	+	+	+	+	– (?)	+
(2) Comparable subgroups at baseline	–	+	+ (?)	+	+	+	+	+	+	+	+	+	+	–	+	+
(3) Blinded care provider	+	–	– (?)	+ (?)	– (?)	–	–	+	– (?)	–	– (?)	+ (?)	–	–	–	–
(4) Correction for attention	+	+	+	+	+	+	+	–	–	+	+	–	+	+	+	+
(5) Acceptable compliance	+	– (?)	?	?	+ (?)	– (?)	– (?)	?	?	–	+ (?)	+	+	+ (?)	+ (?)	+
(6) Blinded patient	–	–	+	– (?)	– (?)	–	–	– (?)	– (?)	– (?)	–	– (?)	–	–	?	–
(7) Acceptable withdrawals during intervention period	+	+	+	–	+ (?)	+	+	+	+ (?)	+	+	+	–	+	+	–
(8) Blinded outcome assessor	+	+	+	+	– (?)	+ (?)	+	+	+	+	+	+	+	+	+	+
(9) Relevance measures	+	+	+	+	+	– (?)	+	+	+	+	+	+	+	+	+	+
(10) Timing assessment	–	–	–	–	–	–	–	+	–	+	–	–	+	–	+	+
(11) Intention to treat analysis	?	– (?)	+ (?)	+ (?)	– (?)	– (?)	– (?)	+ (?)	+ (?)	+	+	+ (?)	+	–	– (?)	+
Total with info: total indep. review	7 (7)	6 (6)	8 (6)	6.5 (4.5)	5.5 (3, 5)	5 (4)	6 (6)	8 (7)	6 (4)	8 (8)	8 (7)	8 (6)	8 (8)	6 (5)	7.5 (6, 5)	8 (8)

Each criterion was scored either positive (+, 1 point), negative (–, 0 points), or unclear (?, 0 points). If the score changed after additional information from the authors or earlier confirmed data from other reviews were retrieved, then the initial score from the independent reviewers is shown between brackets.
A maximum score of 11 points per study could be achieved (1 point for the items 2–11; ½point for the items 1a and 1b).
The last row of the table shows the total score on the AMCL for all 16 included studies. The top number is the score after additional information from the authors or earlier confirmed data from other publications had been processed. The lower row shows the scores based on information from the original articles only.

Table 2 | Overview of study characteristics of included RCTs: stroke and Parkinson's disease population.

Study	Method/ population	Intervention	Measurement instruments, moments and follow-up on physical recovery	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition or emotion reported side-effects
STROKE POPULATION					
Page et al., 2001	Randomized controlled trial N total: 13 N (EG): 8 N (CG): 5 Mean age, SD (years): Total: 64.6 ± 14.6 Time post-stroke (months): EG: range: 2–11 CG: range: 3–11	*MP added to therapy* Both groups: - 6 wk intervention period, 3×/wk 60 min - 30 min upper limb and 30 min lower limb Experimental group: - Daily imagery by tape; 3×/week at home, 2×/week in the clinic - Content tape: 2–3 min relaxation, 7 min MP of ADLs, 2 min refocusing - Three different scripts, 1 for every 2 wk (reaching for and grasping a cup or object, turning a page in a book, proper use of a pencil or pen) - Kinesthetic and visual imagery Control group: Tape: 10 min; information about stroke (both at home and in the clinic)	Primary outcome and primary outcome measure: - ARAT and FM Timing: - Pretest, posttest 6 wk after the start of the intervention - No follow-up	MP added to therapy may have effects on selectivity and ability of the arm and hand No test for significance was performed	Interviews and logs were used but showed no side-effects or effects on cognition/emotion
Liu et al., 2004	Prospective randomized controlled trial N total: 46 N (EG): 26 N (CG): 20 Mean age, SD (years): EG: 71.0 ± 6.0 CG: 72.7 ± 9.4 Mean time post-stroke, SD (days): EG: 12.3 ± 5.3 CG: 15.4 ± 12.2	*MP embedded in therapy* Both groups: - 3 wk 5×/week for 60 min: PT - 3 wk intervention period, 5×/wk for 60 min with either experimental or control intervention by an OT - Tasks: 15 trained functional tasks including household, cooking and shopping tasks, standardized for all patients of the experimental group - First week easy tasks such as laundry folding, third week: shopping, taking transportation Experimental group: - Daily imagery - First week: analyzing task sequences (motor planning) - Second week: problem identification through MI - Third week: practicing - Kinaesthetic and visual imagery was used Control group: - Daily OT conventional functional retraining program - Same dose as intervention MP	Primary outcome and primary outcome measure: - Patient performance on tasks using a 7-point Likert Scale (trained and untrained tasks) Secondary outcome and secondary outcome measure: - FM - CTT Timing: - Pre-test, post-test 3 wk after the start of the intervention - Follow-up 1 month after post-test	MP might improve the execution of both trained and untrained tasks	MP group showed significantly greater improvement CTT (subscale) score across time than control group, possibly indicating increased attention and sequential processing

(Continued)

Table 2 | Continued

Study	Method/ population	Intervention	Measurement instruments, moments and follow-up on physical recovery	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition or emotion Reported side-effects
Page et al., 2005	Randomized controlled trial N total: 11 N (EG): 6 N (CG): 5 Mean age, SD (years): Total: 62.3 ± 5.1 Mean time post-stroke (months): N total: 23.8 (range: 15–48)	*MP added to therapy* Both groups: - 6 wk intervention period, 2×/wk 30 min OT apart from intervention - Task: functional movements of ADLs using affected arm, standardized for all patients of the experimental group Experimental group: - MP by tape after physical practice for 30 min: 5 min relaxation, 20 min MP, 3–5 min refocusing - Internal, cognitive polysensore images were suggested Control group: - Tape: 30 min; progressive relaxation (Jacobson)	Primary outcome and primary outcome measure: - MAL - ARAT Timing: - Twice a pre- and once a posttest 6 wk after star of the intervention - No follow-up	MP added to therapy as usual may have effects on the use and ability of the arm and hand	–
Page et al., 2007	Randomized placebo-controlled trial N total: 32 N (EG): 16 N (CG): 16 Mean age, SD (years): EG: 58.69 ± 12.86 CG: 60.38 ± 14.17 Mean time post-stroke, SD (months): EG: 38.81 ± 25.86 CG: 45.19 ± 43.56	*MP added to therapy* Both groups: - 6 wk intervention period, 2×/wk 30 min physical therapy apart from MP - Task: functional movements of ADL using affected arm - Three versions: 1 for every 2 wk Experimental group: - MP by tape: 5 min relaxation, 20 min MP, 3–5 min refocusing - Internal, cognitive polysensore images were suggested - 1st person view - Kinaesthetic and visual imagery were used Control group: - Tape: 30 min; progressive relaxation (Jacobson)	Primary outcome and primary outcome measure: - FM (upper extremity) - ARAT Timing - Pre-test twice, post-test 1 wk 6 wk after the start of the intervention - No follow-up	MP added to therapy as usual may have effects on selectivity and ability of the arm and hand	–

(Continued)

Table 2 | Continued

Study	Method/ population	Intervention	Measurement instruments, moments and follow-up on physical recovery	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition or emotion Reported side-effects
Muller et al., 2007	Pre-set randomized controlled trial N total: 17 N (EG1): 6 N (EG2): 6 N (CG): 5 Mean age, SD (years): N total: 62 ± 10 Mean time post-stroke, SD (days): Total: 28.7 ± 21.2	*MP added to therapy* All groups: - 4 wk intervention period, 5×/wk 30 min therapy Experimental group1: MENTAL - First session: video-taped finger movement sequence: execute movement until correct order was completed - Thereafter: short refreshment by video followed by only mental rehearsals - Kinaesthetic and visual imagery were used Experimental group2: MOTOR - Perform training task with the affected hand Control group: - Physical therapy	Primary outcome and primary outcome measure: - Jebsen Test (slope differences) - Pinch Grip (slope differences) Timing - 2-week pre-testing - 1-week post-testing 4 wk after the start of the intervention - No follow-up	No differences between the two experimental groups (MOTOR and MENTAL) - Improvement within both experimental groups on all subscales for upper limb use. - Significant differences between both the MOTOR and MENTAL groups on the one hand and the control group on the other in pinch grip and two subscales of the Jebsen Test ("writing" and "simulated feeding")	-
Liu et al., 2009	Randomized controlled trial N total: 35 N (EG): 18 N (CG): 17 Mean age, SD (years) EG: 70.8 ± 9.3 CG: 69.7 ± 7.4 Mean time post-stroke, SD (days): EG: 12.2 ± 5.1 CG: 12.3 ± 7.4	*MP embedded in therapy* Both groups: - 3 wk 5×/week for 60 min: PT - 3 wk intervention period, 5×/wk for 60 min with either experimental or control intervention by an OT - Tasks: 15 trained functional tasks including household, cooking and shopping tasks, standardized for all patients of the experimental group - Each wk, 5 tasks with similar level of difficulty were covered, progressing from the easiest to the most difficult Experimental group: - MP; 5×/wk 60 min - MP involved patients truncating, self-reflecting, feedback, mentally rehearsing combined with performing the activity - Kinaesthetic and visual imagery were used Control group: - Control for attention; 5×/wk 60 min (same dose as MP) - Use of a demonstration-then-practice method	Primary outcome measure: - Performance gains; measuring instrument not mentioned (NRS or Likert Scale) Timing: - Pre-test, post-test 3 wk after the start of the intervention - No follow-up	MP had effect on most of the complex tasks trained: - In 4/5 trained tasks in familiar environment - In 3/5 trained and 2/3 untrained tasks in novel environment MP might improve the execution of both trained and untrained tasks	Patients in the MP group seemed to be more able to form cognitive mapping of routes and plan actions in unfamiliar surroundings (effects on cognition)

(Continued)

Table 2 | Continued

Study	Method/ population	Intervention	Measurement instruments, moments and follow-up and outcome on physical level	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Liu, 2009	Single-blind randomized controlled trial N total: 34 N (EG): 17 N (CG): 17 Mean age, SD (years): EG: 70.4 ± 9.8 CG: 68.1 ± 10.5 Mean time post-stroke, SD (days): EG: 12.3 ± 5.3 CG: 12.3 ± 7.4	*MP added to therapy* Both groups: - 3 wk daily PT for 60 min - 3 wk intervention period, 5×/wk for 60 min with either experimental or control intervention by an OT - Tasks: 15 trained functional tasks including household, cooking and shopping tasks, standardized for all patients of the experimental group - Each wk, 5 tasks with similar level of difficulty were covered, progressing from the easiest to the most difficult Experimental group: - MP: 5×/wk 60 min of which 30 min actually performing the task - MP (30 min) involved self-reflecting and mental imaging - Kinaesthetic and visual imagery were used Control group: - Control for attention: 5×/week for 60 min (same dose) - Use of a demonstration-then-practice method	Primary outcome measure: - 7-point Likert scale Secondary outcome and secondary outcome measure: - FM - Cognistat Timing: - Pre-test, post-test 3 wk after the start of the intervention - No follow-up	MP had effect on most of the complex tasks trained: - In 3/5 trained tasks in primary outcome measures in familiar environment - in 5/5 trained tasks in novel environment MP improved the execution of both trained and untrained tasks. This might indicate that patients in the experimental group were able to generalize learned skills to new situations better than the control group	No differences between groups were measured with the Cognistat Patients in the MP group seemed to be more able to form cognitive mapping of routes and plan actions in unfamiliar surroundings (effects on cognition)

(Continued)

Table 2 | Continued

Study	Method/ population	Intervention	Measurement instruments, moments and follow-up and outcome on physical level	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Page et al., 2009	Randomized controlled trial N total: 10 N (EG): 5 N (CG): 5 Mean age (years): EG: 58.4 (range: 48–72) CG: 64.4 (range: 56–79) Mean time post stroke (months): EG: 26.4 (range: 13–45) CG: 30.6 (range: 17–42)	*MP added to therapy* Both groups: - 10 wk intervention period - Modified constrained-induced therapy (5 h/day, 5 days/wk) - 3 days/wk, 30 min therapy (functional activities) Experimental group: - MP: 10 wk, directly after therapy (3×/wk 30 min) by tape - 5 different tapes (each for 2 wk) with activities of daily living (practiced in therapy) - Homework: daily cognitive rehearsal - Visual and/or kinaesthetic imagery (patients' preference) was used Control group: - Therapy as usual - Tapes were self-administered - Homework on functionally assigned relevant activities was given	Primary outcome measure: - ARAT - FM (upper extremity) Timing: - Pre-test twice, post-test 11 wk after the start of the intervention - Follow-up 3 months after the start of the intervention	Larger score changes on the ARAT and FM in the experimental group compared to the control Differences between groups in favor of the experimental group at post-test but not at follow-up on both the ARAT as FM No test for significance was performed	-
Riccio et al., 2010	Randomized single-blind cross-over study N total: 36 N (GA): 18 N (GB): 18 Mean age (years): GA: 60.17 (range 34–75) GB: 60.06 (range 32–75) Mean time post-stroke (weeks): GA: 7.33 (range 4–12) GB: 7.44 (range 4–12)	*MP added to therapy* Both groups: - 6 wk intervention period conventional neurorehabilitation 5×/wk, 3 h/day Experimental group A: - First 3 weeks only conventional neurorehabilitation - Second 3 weeks MP: 1×/wk 60 min (twice a day 30 min) - MP in a separate quiet room involved relaxation and listening to an audio CD - Activities of the upper limbs, like placing the forearm on the table, were imagined - Kinaesthetic imagery was used Experimental group B: - First 3 weeks MP: 1×/wk 60 min (twice a day 30 min) - MP in a separate quiet room involved relaxation and listening to an audio CD - Activities of the upper limbs, like placing the forearm on the table, were imagined - Kinaesthetic imagery was used - Second three weeks only conventional neurorehabilitation	Primary outcome measure: - MI (upper limb) - AFT (FAS and time in s) Timing: - Pre-test, in-between-assessment 3 wk (before cross-over) and post-test 6 wk after the start of the intervention - No follow-up	Group B improved statistically significantly more on all tests at the in-between-assessment At post-test, after group A received MP too, no differences between groups existed anymore	–

(Continued)

Table 2 | Continued

Study	Method/ Population	Intervention	Measurement instruments, moments and follow-up and outcome on physical level	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Bovend'Eerdt et al., 2010	Single blind randomized controlled trial N total: 30 N (EG): 15 N (CG): 15 Mean age, SD (years): EG: 62.3 ± 11.75 CG: 50.6 ± 16.48 Mixed population: - Stroke: 14 (EG)/14 (CG) - TBI: 0 (EG)/1 (CG) - MS: 1 (EG)/0 (CG) Mean time since onset, SD (weeks): EG: 15.9 ± 17.25 CG: 21.8 ± 15.17	MP *embedded* in therapy Both groups: - Standard physical- and occupational therapy as usual - 5 weeks intervention period - Homework: from the second half of the intervention period both groups were encouraged to practice at home for at least 5 min/day Experimental group: - MP integrated in therapy - At least 3×/week for first 2 weeks and 2×/weeks for the last 2 weeks (total time imagery ∼6.5 h) - A framework for imagery was used - Therapists were trained to teach and monitor MP - Kinaesthetic and visual imagery were used Control group: - Therapy as usual - Control for attention (same dose)	Primary outcome measure: - Goal attainment scale Secondary outcome measure: - BI - RMI - TUG - NEADL - ARAT - A custom-developed questionnaire (Imagery Questionnaire) on patient's confidence and perceived effort Timing: - Pre-test, post-test 6 wk after the start of the intervention - Follow-up 12 wk after the start of the intervention	No conclusion: Compliance of therapists and patients was too low	–

(Continued)

Table 2 | Continued

Study	Method/Population	Intervention	Measurement instruments, moments and follow-up and outcome on physical level	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Ietswaart et al., 2011	Randomized controlled trial N total: 121 N (EG): 39 N (placebo CG): 31 N (normal care CG): 32 Mean age (years): EG: 69.3 Placebo CG: 68.6 Normal care CG: 64.4 Mean time post-stroke, SD (days): EG: 80.2 ± 55.0 Placebo CG: 90.8 ± 63.4 Normal care CG: 80.5 ± 62.7	*MP added to therapy* All groups: - Therapy as usual - 4 weeks of intervention period, 3×/wk 45 min Experimental group: - MP: 45 min; 30 min actively imagining (elementary movements, ADL), 10 min active motor imagery (using mirrors and videos), 5 min for a covert form of motor imagery activity (mentally rotating pictures of hands) - Kinaesthetic imagery was used Attention-placebo control group: - Placebo: 40 min; 25 min active visual and sensory imagery, 10 min cognitive inhibition, 5 min watching optical illusions of motion - Control for attention (same dose) Normal care control group: - Therapy as usual	Primary outcome measure: - ARAT Secondary outcome measure: - Grip strength, hand-function - BI - Dynamometer, manual dexterity performance - Modified functional limitation profile Timing - Pre-test, post-test 5 wk after baseline - No Follow-up	No effects were found on any outcome measure An added mental practice intervention has similar effects a controlled therapy as usual	–
Welfringer et al., 2011	Randomized controlled trial N total: 30 N (EG): 15 N (CG): 15 Mean age, SD (years): EG: 56.3 ± 11.2 CG: 57.1 ± 11.3 Mean time post-stroke, SD (months): EG: 3.2 ± 1.5 CG: 3.4 ± 2.8	MP *added* to therapy Both groups: - Standardized rehabilitation 4×/wk, 45 min - 3 weeks intervention period Experimental group: - MP added to therapy - Two daily half-hour sessions (total 28–30 sessions) - Relaxation, followed by mental practice of positions of the contralesional upper limb: four positions and six sequences (simple and complex movements) - Each exercise up to 10 repetitions - Kinaesthetic imagery was used Control group: - No supplementary intervention	Primary outcome measure: - Neglect tests: bells cancellation test, drawing test, and text-reading task Secondary outcome measures: - Representation test (adapted): R-MIQ - Arm-Hand-Function tests: ARAT and sensation functions General effort to complete a MP session: NRS (1–10) Timing: - Pre-test, post-test 3 wk after the start of the intervention - No follow-up	MP had significant effects for the drawing test and the sensation functions only Overall test results ambiguous Self-perceived benefits of patients high	Negative reported side-effect: - diminished concentration capacity and signs of tiredness at the end training sessions Positive reported side-effects: - all patients reported sensations in the left arm during imagery - increased awareness of the left arm

(Continued)

Table 2 | Continued

Study	Method/ Population	Intervention	Measurement instruments, moments and follow-up and outcome on physical level	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Braun et al., 2012	Multicentre randomized controlled trial N total: 36 N (EG): 18 N (CG): 18 Mean age, SD (years): EG: 77.7 ± 7.2 CG: 77.9 ± 7.4 Mean time post-stroke, SD (weeks): EG: 6.1 ± 2.7 CG: 4.8 ± 3.3	*MP embedded in therapy* Both groups: - 6 wk intervention period - 6 wk physical therapy; according Dutch multidisciplinary guidelines for stroke rehabilitation - Task: drinking from a cup, walking (standardized) - Optional tasks: self-selected arm and leg activities Experimental group: - MP: 6 wk, 5×/wk 30 min - MP was given according to a 4-step framework involving explaining and developing imagery techniques before applying them - Visual and/or kinaesthetic imagery (patients' preference) was used Control group: - Therapy as usual - Control for attention: homework (same dose)	Primary outcome measure: - Numeric Rating Scale (1-10): patients' and therapists' perceived effect on performance of daily activities Secondary outcome measure: - MI - NHPT - BBS - BI - 10 m-walking test - RMI Timing: - Pre-test, post-test 6 wk after the start of the intervention - Follow-up 6 months after the start of the intervention	No differences between groups short or long-term An embedded mental practice intervention in therapy as usual in nursing home residents has similar effects as therapy as usual in which there was control for attention	Positive side-effect: - Increased feeling of autonomy Negative side-effect: - MP costs too much effort to perform (drop out)
Schuster et al., 2012	Randomized controlled trial N total: 39 N (EG1): 13 N (EG2): 12 N (CG): 14 Mean age, SD (years): EG1: 65.8 ± 10.2 EG2: 59.7 ± 13.0 CG: 64.4 ± 6.8 Mean time post-stroke, SD (years): EG1: 2.9 ± 1.9 EG2: 4.3 ± 3.6 CG: 3.5 ± 3.9	*MP added to or and embedded in therapy* Both groups: - 2 weeks of intervention period - physiotherapy: 6 sessions 25–30 min Experimental 1 group (embedded): - MP was embedded in the six sessions - Total intervention time: 45–50 min - PETTLEP-framework was used; physical/emotion, timing, environment, task/learning/perspective - Complete motor task was divided into its 13 stages - Each part was imagined5× before physical performance - Kinaesthetic and visual imagery were used Experimental 2 group (added): - MP by tape: 3.5 min relaxation, 14.5 min MP, 2 min refocusing. - Total intervention time: 45–50 min - Kinaesthetic and visual imagery were used Control group: - Physiotherapy - Control for attention: tape; 17 min; 3.5 min relaxation, 11.5 min information about stroke, 2 min refocusing	Primary outcome measure: - Time difference in seconds to perform the motor task from pre- to post-intervention Secondary outcome measures: - Help needed to perform the task using CMSA Achieved stage of motor task - BI - BBS - Computer-based Imaprax questionnaire - KVIQ - Activities-Specific Balance Confidence Scale, intrinsic motivation evaluated in patient's diary Timing: - Twice at baseline, before intervention, post-test 2 wk after the start of the intervention - Follow-up after 2 wk	No between group differences were found A mental practice intervention embedded in or added to therapy as usual has similar effects as therapy as usual	Logs were used but showed no side-effects or effects outside of the physical domain

(Continued)

Table 2 | Continued

Study	Method/ Population	Intervention	Measurement instruments, moments and follow-up and outcome	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
PARKINSON'S DISEASE					
Tamir et al., 2007	Randomized controlled trial N total: 23 N (EG): 12 N (CG): 11 Mean age, SD (years): EG: 67.4 ± 9.7 CG: 67.4 ± 9.1 Mean duration of PD, SD (years): EG: 7.4 ± 3.1 CG: 7.8 ± 4.5	*MP embedded in therapy* Both groups: - 12 wk intervention period, 2×/wk 60 min physical therapy - Protocol of 3 parts (each 15–20 min): (1) callisthenic exercises (2) crucial motor tasks and (3) relaxation exercises - Emphasis on improving the smooth performance of tasks Experimental group: - MP was performed within the second part of the protocol (crucal motor tasks) and during the relaxation period (previously practiced tasks were rehearsed mentally) - Kinaesthetic and visual imagery were used Control group: - The exercises were performed physically and relaxation exercises were executed (control for attention, same dose)	Primary outcome measure: - TUG Secondary outcome measures: - Standing up and laying down - Turning in place 360° - Tandem stance - Functional reach and shoulder tug - UPDRS Cognitive tasks: - Clock drawing - Stroop test (part A and B) Timing: - Pre-test, post-test 12 wk after the start of the intervention - No follow-up	MP had significant differences in - TUG - Getting up from a chair or from a supine lying position - Number of steps taken to complete the turn - UPDRS section mental (between group-differences)	Cognitive level: + Significant differences in - Stroop test part B indicating an increase in attention and concentration (clinical relevance unknown as same amount of improvement in both groups, but an increase in test errors in 4 subjects of the control contrary to 1 in the experimental group) Some indication that imagery might increase motivation and arousal and reduce depression

(Continued)

Table 2 | Continued

Study	Method/ Population	Intervention	Measurement instruments, moments and follow-up and outcome	Conclusion with regard to the effects of MP on physical recovery	Effects reported on cognition/emotion Reported side-effects
Braun et al., 2011a	Multicentre randomized controlled trial N total: 47 N (EG): 25 N (CG): 22 Mean age, SD (years): EG: 70 ± 8 CG: 69 ± 8 Mean duration of PD, SD (years): EG: 5.2 ± 5.0 CG: 6.6 ± 7.8	MP *embedded* in therapy Both groups: - 6 wk intervention period - Physical therapy; 1×/wk 60 min (groups) or 2×/wk 30 min (individuals), according Dutch guidelines for PD - Task: locomotor tasks (walking, standing up from the floor or a chair) Experimental: - MP: 1×/wk 20 min (groups) or 2×/wk 10 min MP (individuals) - MP was given according to a 4-step framework involving explaining and developing imagery techniques before applying them - Visual and/or kinaesthetic imagery (patients' preference) was used Control group: - Control: therapy as usual - Control for attention: progressive relaxation (Jacobson, same dose)	Primary outcome measure: - VAS (walking performance), patients' and therapists' perceived effect on performance Secondary outcome measures: - TUG - 10 m walk test Timing: - Pre-test, post-test 6 wk after the start of the intervention - Follow-up 12 wk after the start of the intervention	No differences between groups at short- or long-term An embedded mental practice intervention in therapy as usual has similar effects as therapy as usual with relaxation	Negative side-effect: - MP costs too much effort to perform (drop out) - Thinking about motor actions is too confronting (drop out)

Abbreviations: ADL, Activities of Daily Living; AFT, Arm Functional Test; ARAT, Action Research Arm Test; BBS, Berg Balance Scale; BI, Barthel Index; CG, Control Group; CMSA, Chedoke-McMaster Stroke Assessment; CTT, Color Trails Test; EG, Experimental Group; FAS, Functional Ability Scale; FM, Fugl-Meyer assessment; h, hours; min, minutes; KVIQ, Kinesthetic and Visual Imagery Questionnaire; MAL, Motor Activity Log; MI, Motricity Index; MP, mental practice; NEADL, Nottingham Extended Activities of Daily Living; NHPT, Nine Hole Peg Test; NRS, Numeric Rating Scale; OT, Occupational Therapy; PT, Physiotherapy; RMI, Rivermead Mobility Index; R-MIQ, Revised-Movement Imagery Questionnaire; SD, Standard Deviation; TUG, Timed Up and Go; UPDRS, Unified Parkinson's disease Rating Scale; VAS, Visual Analogue Scale; wk, weeks.

et al., 2007; Liu, 2009; Bovend'Eerdt et al., 2010; Braun et al., 2011a, 2012; Schuster et al., 2012).

Based on these qualitative descriptions it seems that different kind of interventions may have potential effects on activities (e.g., embedded and added mental practice were both reported effective and ineffective in different studies).

EFFECTS ON COGNITION OR EMOTION AND SIDE-EFFECTS

Five studies reported effects on cognition (Liu et al., 2004, 2009; Tamir et al., 2007; Liu, 2009; Welfringer et al., 2011) which were measured with the Stroop test (part B) in participants with Parkinson's disease (Tamir et al., 2007), the Color Trails Test (CTT; Liu et al., 2004) and the Cognistat (Liu, 2009) in participants after stroke (**Table 2**). Participants with Parkinson's disease seemed to have an increase in attention and concentration after the mental practice intervention period (Tamir et al., 2007). In the studies by Liu et al. (2004, 2009); Liu (2009) the mental practice intervention involved strategy training and participants after stroke seemed to be more able to form cognitive maps of routes and plan actions in unfamiliar surroundings compared to the participants in the control group. Earlier positive findings on the CTT were however not repeated in a later study using the Cognistat (Liu et al., 2004; Liu, 2009).

Positive observed side-effects reported in the stroke trials were increased autonomy (Braun et al., 2012) and increased sensations in and awareness of the left arm (Welfringer et al., 2011). In Parkinson's disease research there was some indication that imagery might increase motivation and arousal and reduce depression (Tamir et al., 2007).

Two studies reported acute adverse side-effects of mental practice (Braun et al., 2011a, 2012) like "too much effort," "not worthwhile," and "too confronting." Some participants after stroke showed diminished concentration and signs of tiredness at the end of mental practice training sessions (Welfringer et al., 2011).

DATA SYNTHESIS OF THE META-ANALYSIS

The meta-analysis was conducted using a selection of the studies in stroke in which the same physical outcome measurement instruments were used (**Table 3**).

A meta-analysis in participants with Parkinson's disease was not possible. Both studies use the Timed up and Go as an outcome measure, but Tamir et al. did not report the exact data (only figures provided; Tamir et al., 2007). Several outcome measures which had been used in at least two studies were excluded because of missing data (Motricity Index, Pinch/Hand force; Muller et al., 2007; Riccio et al., 2010). The study of Schuster et al. (2012) was excluded because of clinical important differences between groups at baseline. Six times data could pooled in a meta-analysis. No sensitivity test could be performed as all studies that could be pooled were of at least sufficient quality.

RESULTS ON MOBILITY—RIVERMEAD MOBILITY INDEX

Data were available from two studies (Bovend'Eerdt et al., 2010; Braun et al., 2012) that randomized a total of 64 and 58 participants respectively. Pooling did not lead to significant effects assessed with the Rivermead Mobility Index directly after the intervention ($p = 0.72$; *MD*: −0.82; 95% *CI*: −3.04 to 1.41) nor at follow-up ($p = 0.75$; *MD*: −0.40; 95% *CI*: −2.90 to 2.10).

RESULTS ON ARM-FUNCTION—ACTION RESEARCH ARM TEST (FIGURE 2)

Data were available from seven studies (Page et al., 2001, 2005, 2007, 2009; Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Welfringer et al., 2011) that randomized a total of 197 participants. Due to heterogeneity in the SDs of outcomes SMD and

Table 3 | Overview of used measure instruments that could potentially be used in pooling.

Outcome	ARAT	Pinch	NRS/LS	MI	BBS	BI	10 m	RMI	TUG
STROKE									
Page et al., 2001	×								
Liu et al., 2004			×						
Page et al., 2005	×								
Page et al., 2007	×								
Muller et al., 2007		×							
Liu et al., 2009			×						
Liu, 2009			×						
Page et al., 2009	×								
Riccio et al., 2010				×					
Bovend'Eerdt et al., 2010	×					×		×	×
Ietswaart et al., 2011	×	×				×			
Welfringer et al., 2011	×								
Braun et al., 2012			×	×	×	×	×	×	
Schuster et al., 2012					×	×			
PARKINSON'S DISEASE									
Tamir et al., 2007									×
Braun et al., 2011a			×				×		×

Abbreviations: ARAT, Action Research Arm Test; NRS/LS, Numeric Rating Scale/Likert Scale; MI, Motricity Index; BBS, Berg Balance Scale; BI, Barthel Index; 10 m, 10 m walking test; RMI, Rivermead Mobility Index; TUG, Timed Up and Go. Gray Shading: Data could be pooled.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Bovend'Eerdt et al., 2010	31.7	24.97	15	30.7	23.38	15	18.2%	0.04 [-0.68, 0.76]
Ietswaart et al., 2011	31.51	20.68	39	30.38	20.53	32	21.8%	0.05 [-0.41, 0.52]
Page et al., 2001	40.4	13.4	8	25	11.7	5	11.6%	1.12 [-0.11, 2.35]
Page et al., 2005	43.8	3.09	6	38.7	1.2	5	8.8%	1.91 [0.36, 3.46]
Page et al., 2007	25.81	11.29	16	17.69	13.75	16	18.2%	0.63 [-0.08, 1.34]
Page et al., 2009	42.6	1.2	5	36.4	1.1	5	3.1%	4.86 [1.86, 7.87]
Welfinger et al., 2011	9.6	18.5	15	6.5	16.2	15	18.2%	0.17 [-0.54, 0.89]
Total (95% CI)			**104**			**93**	**100.0%**	**0.62 [0.05, 1.19]**

Heterogeneity: Tau² = 0.33; Chi² = 17.14, df = 6 (P = 0.009); I² = 65%
Test for overall effect: Z = 2.13 (P = 0.03)

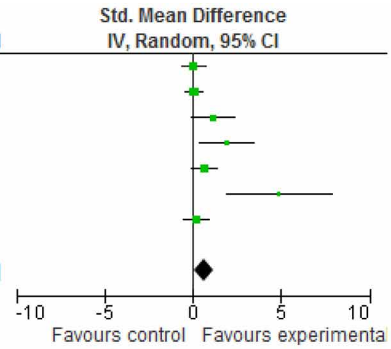

FIGURE 2 | Results of pooling for ARAT: short-term effects. Abbreviations: ARAT, Action Research Arm Test; SD, standard deviation; 95% CI, 95% confidence interval.

random-effect model were used. Pooling led to significant short-term effects on the Action Research Arm Test ($p = 0.03$;*SMD* 0.62; 95% *CI*: 0.05 to 1.19). No data for long-term effects could be pooled.

RESULTS ON FUNCTIONING IN ACTIVITIES OF DAILY LIVING—BARTHEL INDEX

Data of the Barthel Index were available from three studies (Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Braun et al., 2012) on short-term that randomized a total of 135 participants. Pooling did not show significant effects ($p = 0.31$; *MD*: 0.87; 95% *CI*: −0.80 to 2.53). No significant effects were found at follow-up either ($p = 0.75$; MD:0.46; 95% *CI:* − 2.36 to 3.27). Data for long-term effects were available from two studies (Bovend'Eerdt et al., 2010; Braun et al., 2012) that randomized a total of 57 participants. The study of Liu (Liu et al., 2009) used the modified Barthel Index and was therefore excluded from pooling in both meta-analyses.

RESULTS FROM FUNCTIONAL ACTIVITIES—NUMERIC RATING SCALE (FIGURE 3)

Four studies (Liu et al., 2004, 2009; Liu, 2009; Braun et al., 2012) used a numeric rating scale to assess the performance of functional activities. Two studies were excluded from the analyses because they did not provide any point estimates (Liu, 2009; Liu et al., 2009). The data of the studies by Braun et al. and Liu et al. were pooled using SMD because Braun et al. (2012) used a 10-point scale whereas Liu et al. (2004) used a 7-point scale. Liu et al. provide data of the average score of five activities that was used for the analyses. Braun et al. provided scores of the NRS of drinking, walking, and two self-chosen activities. We used the data of the most promising result (biggest different between the experimental and the control group) this was the score of the self-chosen activity for the lower limb. Data of 78 participants could be pooled and a marginal significant overall effect on short-term was found. ($p = 0.04$; *SMD* 0.9; 95% *CI:* 0.04 *to* 1.77). No long-term data could be pooled.

DISCUSSION

This present review included 16 randomized controlled trials (14 in stroke and two in Parkinson's disease) involving 491 participants (of which 70 in Parkinson's disease) and shows some benefits of a mental practice intervention on arm hand ability (Page et al., 2001, 2005, 2007, 2009; Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Welfringer et al., 2011) and mobility (Liu et al., 2004; Braun et al., 2012) after stroke. Of the 14 identified studies only 6 showed overall effects in favor of mental practice.

No firm conclusions can be drawn from the existing evidence with regard to the effectiveness of mental practice in participants with Parkinson's disease. No randomized controlled trials within the multiple sclerosis target group were found. Two recently published non-randomized studies investigated the mental practice ability of patients with multiple sclerosis (Heremans et al., 2012a,b). There seems to be a potential use of mental practice in patients with multiple sclerosis. The studies reported in this review remain small (sub groups ranging from 5 to 39 participants), the populations studied vary greatly in most clinical domains, and the outcomes studied also differ a lot. The methodologic quality of the studies ranged from 3.5 to 8 points on the AMCL assessment scale after blinded assessment and also after additional information from the authors was taken into account. This review also finds some evidence for effects on cognition and emotion (e.g., effects on attention, plan actions in unfamiliar surroundings) and reports several observed side-effects (e.g., might increase motivation and arousal and reduce depression, but may also lead to diminished concentration and irritation).

Four recent zero trials (Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Braun et al., 2012; Schuster et al., 2012) have been added to the body of knowledge on mental practice ($n =$ 226), accounting for about half of the total number of participants within all 14 included trials in stroke. Within these zero trials the sample sizes are bigger and more heterogeneous. In addition, more measures on activity level in more general sense were used within these later trials (Barthel Index, BI, and Rivermead Mobility Index, RMI). One could hypothesize that the effects of mental practice are mainly related to aspects as velocity, precision, and coordination of a movement. Improvement in these specific effects of mental practice are perhaps not or hardly detectable with these more generic measures contrary to f.i. the ARAT. In the ARAT and the NRS meta-analyses

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Braun et al., 2012	7.19	1.6	16	6.38	1.9	16	48.8%	0.45 [-0.25, 1.15]
Liu et al., 2004	5.3	1	26	4	0.9	20	51.2%	1.33 [0.68, 1.98]
Total (95% CI)			**42**			**36**	**100.0%**	**0.90 [0.04, 1.77]**

Heterogeneity: Tau² = 0.27; Chi² = 3.28, df = 1 (P = 0.07); I² = 70%
Test for overall effect: Z = 2.04 (P = 0.04)

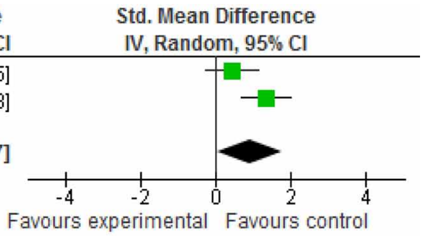

FIGURE 3 | Results of pooling for NRS: short-term effects. Abbreviations: NRS, Numeric Rating Scale; SD, standard deviation; 95% CI, 95% confidence interval.

outcome of both zero and positive trials were pooled, leading to small effect sizes for mental practice in these outcome measures.

Imagery research is still booming and after our search was completed (June 2012) results of new trials were published (f.i. two recent studies on the effects of imagery on gait (Cho et al., 2012; Guttman et al., 2012)). These studies however remain relatively small, but adding new trials to the models could still overturn the results (Langhorne et al., 2009).

STUDY LIMITATIONS

There is a possibility that studies were missed due to inconsistency in terminology used in databases (e.g., mental practice, motor imagery, movement imagery).

The varied clinical populations in this review can be seen as a limitation. This review however does summarize the existing information in neurorehabilitation about a widely used intervention, which will facilitate the exchange of existing knowledge and evidence between professionals working with different target populations. Reviews covering the evidence for specific interventions in multiple target groups, like the recently published one by Newman and Barker (2012) on supported standing, will help professionals get a better understanding of the intervention and potential (side-) effects.

Using assessment scales in general and therefore also the AMCL for rating methodologic quality leads to some practical issues. Blinding of therapists and patients is often not possible in therapeutic interventions like mental practice. If therapists instruct the patients they are not blind to the type of intervention they are providing. The same accounts for the patients when they are asked to actively participate in an intervention. In randomized controlled trials in which therapeutic interventions (e.g., physiotherapy and occupational therapy) are researched the assessment of the randomized controlled trials with any assessment scale will be lower than in for instance pharmaceutical studies. The highest possible score on the AMCL of 11 points will decrease in many therapeutic studies by 2 points, as double blinding is often not possible.

Different assessment tools were used to rate the quality of the included studies (PEDro (Nilsen et al., 2010; Barclay-Goddard et al., 2011), AMCL (Braun et al., 2006), JADAD (Cha et al., 2012)) in earlier reviews. The PEDRO and AMCL are derived from the Delphi list and therefore interrelated (Olivo et al., 2008). The JADAD is a shorter list, most used even though it was not originally developed for therapeutic studies (Olivo et al., 2008). Sometimes the studies within the reviews were categorized into lower and high quality studies (Braun et al., 2006; Zimmermann-Schlatter et al., 2008; Cha et al., 2012) and sometimes the authors of trials were contacted to provided additional information (Barclay-Goddard et al., 2011).

We contacted the authors to clarify the criteria on which a question mark was scored after the blinded reviewing assessment by the independent reviewers was performed. The quality assessment of identical studies may therefore vary within the different reviews as scores on assessment tools normally go up after additional information is retrieved. In one review the quality criteria for assessment of the identified studies were chosen by the reviewers (Zimmermann-Schlatter et al., 2008). These differences make it harder to compare the results and recommendations from the reviews.

Good reporting of trials is important to understanding changes and effects of mental practice and therefore ongoing attention to high quality study reports is required (Barclay-Goddard et al., 2011). Guidelines, like the CONSORT statements are essential to achieve this.

The biggest problem of researching mental practice is the lack of consensus on the definition and concept of the intervention. Heterogeneity within the intervention protocols and outcomes makes it impossible to conduct an overall pooling and thus to come to an overall conclusion.

Results from pooling based on identical outcome measures should be interpreted with caution because of the heterogeneity in study populations. Also, results from meta-analyses depend very much on the data (and models) used. We decided to base the decision on which model to use on the measurement instruments (identical instruments or instruments measuring the same construct) and on the variance in SDs across the included studies. The downside of this flexibility in data/model choice is that it is harder for the reader to follow what has been done in the analysis. The biggest and in our opinion more important advantage is that the outcome is less misleading. Big variation in SDs across studies reflect differences in the real variability of outcomes and the use of MD would in our case suggest potential effects which are probably not there. The study by Ietswaart et al. (2011) with the largest population would for instance have the lowest weight in the meta-analysis and studies with relatively small sample sizes would determine outcome for more than 80%. We tried to correct for this heterogeneity in the analysis and we used change scores instead of effect sizes which might explain to some extend why our results are less optimistic than the meta-analysis by Cha et al. (2012). In the meta-analysis by Cha et al. mental practice combined with exercise therapy had an even bigger effect size (ES 0.51; moderate) then augmented therapy alone (Cha et al., 2012). Two other reviews (Nilsen et al., 2010; Barclay-Goddard et al., 2011) performed statistical analyses to synthesize the evidence of six (Barclay-Goddard et al., 2011) and four (Nilsen et al., 2010) studies. Differences in statistical analysis approaches should be taken into account when interpreting and comparing the results.

Publication bias is a potential weakness in all systematic reviews, as positive or statistically significant findings are more likely to be published than small trials with non-significant or negative findings (Thornton and Lee, 2000). The funnel plot of the ARAT showed indication for publication bias (results not presented) and should therefore be interpreted with care. Barclay-Goddard et al. (2011) identified some risk of bias with regard to concealment of allocation and blinding. Cha et al. (2012) did not report any significant publication bias in their investigation.

STRENGTHS AND LIMITATIONS OF PAST STUDIES

Determining effects of complex interventions like mental practice is complicated (Braun et al., 2011b). A systematic way of assessing the potential of mental practice could be through the four steps suggested by the Medical Research Council (Craig et al., 2008). Until now, most research has been performed in the first two steps of this model: "determining the working mechanisms" and "piloting." Fundamental research has shown that mental practice can be performed in patients with neurological conditions and showed that the underlying mechanism is also working in at least parts of the patient populations.

The past 5 years more research has been published on techniques that might assist in monitoring and implementing imagery treatments, like tests (e.g., chronometry, hand-rotation-test; Malouin et al., 2008a; Simmons et al., 2008) and questionnaires (e.g., KVIQ; Malouin et al., 2007, 2008b). Mental practice has been explored in different clinical situations and contexts and a range of different types of intervention, assessed with different measures, have been studied. However, the predictive value of these tests has not been established yet. So we do not know for sure if people who can image according to questionnaires and tests will also benefit from it and whether participants who are at first unable to image, are able to learn and potentially benefit from imagery. In addition, if imagery tests are used as a selection tool patients who are unable to perform these tests are often excluded from research. That is why the study by Welfringer et al. (2011) is of value. Although the results should be interpreted with great caution because participants in the control group did not receive supplementary therapy on top of therapy as usual to control for mental practice, it is until now the only mental practice randomized controlled trial in patients with neglect. Researching feasibility and effects in sub groups that are normally excluded from research will tell us more about whether mental practice can be taught and who might benefit.

There are general methodologic issues in rehabilitations trials (Dobkin, 2007) that also should be considered in mental practice studies. The main problem is that almost all studies are underpowered, increasing the chance of type-2 errors. Especially in mono-centered, small trials the samples are not likely to reflect the real-world sample.

RECOMMENDATIONS FOR THE DESIGN OF FUTURE TRIALS

Recent negative trials have shown that not all participants with stroke and Parkinson's disease benefit from mental practice. At this point we do not know how to identify the people who might benefit from mental practice. Sample sizes of future trials should be large enough to enable sub group and dose-response analyses. For dose-response analyses adherence, attendance, and compliance should be reported (Barclay-Goddard et al., 2011). Especially adherence and compliance are difficult to assess as mental practice is an intervention that takes place in the mind and remains covert for the therapist. For adherence to mental practice it is essential that participants can engage in movement imagery. However, there is no perfect test to assess this ability. Combining some tests might provide indicators which then might be related to outcome. Therefore, the imagery ability of every participant should be assessed before and/or after the mental practice intervention.

The mental practice intervention should be well described. Both, short- and long-term effects should be measured with predefined measure instruments to enable comparison of results among different studies. Effects should not only be sought at the physical level, but also on emotion and cognition (Nilsen et al., 2010; Barclay-Goddard et al., 2011). Reporting the opinions on and experiences with mental practice of people with neurological diseases, care-givers, and care professionals will provide valuable information on how to optimize and tailor the mental practice intervention to the patients' needs and abilities. Mixed methods are needed to assess these different components.

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APPENDIX

Table A1 | Amsterdam-Maastricht Consensus List for quality assessment rating criteria.

Item	Rating criteria
(1A) Randomization	Item has a positive score if the concealment of treatment allocation is explicitly described to be randomized (e.g., computer generated block randomization) Note: Quasi-randomization is scored negative (e.g., randomization of dates of birth or day of the week)
(1B) Concealment of allocation	Item has a positive score if explicitly is described that the allocation of the intervention was blinded (e.g., a independent assessor performs the allocation and has no information/influence on who will be allocated to which group)
(2) Comparable sub groups at baseline	Item has a positive score if the study groups are comparable at baseline with the most important prognostic factors (e.g., comparable mean age and standard deviation in the study groups)
(3) Blinded care provider	Item has a positive score if the care provider is blinded regarding treatment allocation (e.g., the care provider is unaware of the content of the intervention*)
(4) Correction for attention; same treatment (dose), co-intervention	Item has a positive score if the different intervention groups have the same treatment dose and if co-interventions are equally divided among the intervention groups. Also, participants in both groups are asked to provide the same information (e.g., fill in logs) and undergo the same tests (battery)
(5) Acceptable compliance	Item has a positive score if participants themselves or therapist and relatives report that the participants followed the given instructions (e.g., through logs, interviews)
(6) Blinded patient	Item has a positive score if patients are blinded regarding treatment allocation and if the method of blinding is appropriate (e.g., the patient is unaware of the treatment content*)
(7) Acceptable withdrawals during intervention period	Item has a positive score if the percentage of patients that drop out of the study does not exceed 10% during the intervention period. Another 10% of loss to follow-up of the remaining sample is set as acceptable for the follow-up period
(8) Blinded outcome assessor	Item has a positive score if the outcome assessors are blinded regarding treatment allocation (e.g., independent raters, who are unaware of the treatment group that the participant is in–preferably checked by asking the rater to predict who is in which group)
(9) Relevance measures	Item has a positive score if the measurement instruments allow answering the research question
(10) Timing assessment	Item has a positive score if the outcome assessment takes place approximately at the same time in all intervention groups. Also, a follow-up period of at least 3 months is set to be acceptable
(11) Intention to treat analysis	Item has a positive score if all randomized patients are reported for all measuring points and are analysed according to the group they were originally randomized to

**Blinding of the care provider and of the patient is not always applicable in physical therapy because of the nature of physical therapy interventions (e.g., manual therapy, exercises). Proper double blinding, therefore, is unlikely to be accomplished for most physical therapy trials (Olivo et al., 2008).*

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Towards the integration of mental practice in rehabilitation programs. A critical review

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Many clinical studies have investigated the use of mental practice (MP) through motor imagery (MI) to enhance functional recovery of patients with diverse physical disabilities. Although beneficial effects have been generally reported for training motor functions in persons with chronic stroke (e.g., reaching, writing, walking), attempts to integrate MP within rehabilitation programs have been met with mitigated results. These findings have stirred further questioning about the value of MP in neurological rehabilitation. In fact, despite abundant systematic reviews, which customarily focused on the methodological merits of selected studies, several questions about factors underlying observed effects remain to be addressed. This review discusses these issues in an attempt to identify factors likely to hamper the integration of MP within rehabilitation programs. First, the rationale underlying the use of MP for training motor function is briefly reviewed. Second, three modes of MI delivery are proposed based on the analysis of the research protocols from 27 studies in persons with stroke and Parkinson's disease. Third, for each mode of MI delivery, a general description of MI training is provided. Fourth, the review discusses factors influencing MI training outcomes such as: the adherence to MI training, the amount of training and the interaction between physical and mental rehearsal; the use of relaxation, the selection of reliable, valid and sensitive outcome measures, the heterogeneity of the patient groups, the selection of patients and the mental rehearsal procedures. To conclude, the review proposes a framework for integrating MP in rehabilitation programs and suggests research targets for steering the implementation of MP in the early stages of the rehabilitation process. The challenge has now shifted towards the demonstration that MI training can enhance the effects of regular therapy in persons with subacute stroke during the period of spontaneous recovery.

Keywords: motor imagery, motor imagery training, mental practice, stroke rehabilitation, motor skill learning, stroke, Parkinson's disease, neurological rehabilitation

INTRODUCTION

The ever-increasing number of publications attests to clinician expectations of mental practice (MP) through motor imagery (MI) as a means of promoting the recovery of motor function (for a review see Malouin and Richards, 2013). MP not only provides a unique opportunity to increase the number of repetitions in a safe and autonomous manner without undue physical fatigue, but it also allows the mental rehearsal of motor tasks when and where the patient wants to, or is able to, practice. Furthermore, MP enables the rehearsal of more demanding or complex motor tasks (e.g., walking, writing) when physical practice is impossible or too difficult. Yet, despite these obvious advantages, MP is a complex mental process that is not readily amenable to be integrated into clinical practice. To date, in most published studies, MP has been used within constrained research environments to meet the requirements associated with research methodology.

As highlighted by several review papers concerning the use of MP in rehabilitation, (van Leeuwen and Inglis, 1998; Jackson et al., 2001; Braun et al., 2006; Dickstein and Deutsch, 2007; Zimmermann-Schlatter et al., 2008; Dijkerman et al., 2010; Malouin and Richards, 2010, 2013) there are marked differences in designs, research protocols, training regimens and outcome measures among the growing number of studies. Despite this heterogeneity, positive effects of MP on motor function have been generally reported. However, Braun et al. (2006), in a systematic review of five selected randomized controlled trials (RCT), stated that although there was some evidence that MP as an adjunct therapeutic intervention had beneficial effects on arm function, they were not able to draw definite conclusions and stated that further research with a clear definition of the content of the MP and standardized outcome measures were needed. In a more recent review that included six studies, Barclay-Goddard et al. (2011) also concluded that the combination of MP with other treatments appeared to be more effective than other treatments alone to improve upper extremity function. Based on their assessment with the PEDro scale, the quality of the evidence was moderate. Likewise, in their systematic review of 15 studies, Nilsen et al. (2010) attested that when MP was added to physical practice (PP), it was an effective intervention. Nevertheless, they also mentioned that further research was needed to identify those patients most likely to benefit from training, the optimal dose, and the most effective protocols.

These reviews, however, did not include the findings originating from recent multicenter RCTs (Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Braun et al., 2012; Timmermans et al., 2013) in subacute patients that have attempted to integrate MI training in regular rehabilitation programs. Not only did the addition of MP to conventional training on all tasks fail to yield better functional outcomes than conventional training, but the low compliance of therapists (Bovend'Eerdt et al., 2010; Braun et al., 2010, 2012) and realities related to patients such as advanced age of those in nursing homes (Braun et al., 2012) point to some of the difficulties encountered when attempting to introduce MP into regular clinical practice. The findings of two recent RCTs, (Ietswaart et al., 2011; Timmermans et al., 2013) did not confirm the additional benefits of including MI training in the rehabilitation program aimed at improving upper limb function. Despite meticulously designed MI training that included a variety of approaches (action observation through mirror therapy, implicit imagery, and self-practice), patients with subacute stroke did not show additional gains in the performance of activities of daily living (ADL) (Ietswaart et al., 2011). Altogether, these latest findings reflect the complexity of integrating MP into regular rehabilitation programs. Thus, this review scrutinizes the current application of MP, and from this analysis proposes a framework for its integration into usual rehabilitation programs.

RATIONALE UNDERLYING MI TRAINING

With the turn of the twenty-first century, we have witnessed the emergence of clinical studies designed to investigate the effects of MP on the relearning of motor skills in persons with stroke. The rationale for using MI training to promote the relearning of motor function arises from research on the functional correlates that MI shares with the execution of physical movements. It is now widely recognized that the duration of mentally simulated actions usually correlates with the duration of real movements (temporal coupling), that the simulation of movements evokes similar autonomic responses and that the imagination of an action or its physical execution engage largely similar neural networks (Decety and Boisson, 1990; Decety et al., 1991; Decety and Jeannerod, 1995; Wuyam et al., 1995; Decety, 1996; Decety and Grèzes, 1999; Lafleur et al., 2002; Malouin et al., 2003; Fusi et al., 2005; Munzert and Zentgraf, 2009; Hétu et al., 2013). These similarities led to the notion of functional equivalence. Thus, real and covert movements during MI obey similar principles and share similar neural mechanisms, likely explaining the beneficial effects of MP on motor performance (Jeannerod, 1995).

MI TRAINING (MP) IN HEALTHY INDIVIDUALS: SKILL LEARNING

Much of the evidence for using MI in the training of motor function is based on findings from studies that examined the effect of MI training in healthy adults (Yue and Cole, 1992; Pascual-Leone et al., 1995; Jackson et al., 2003; Allami et al., 2008; Olsson et al., 2008; Reiser et al., 2011). These studies have shown that MI training *alone* can significantly promote the learning of a novel motor skill, but it is important to keep in mind that such training needs to be very intensive. For instance, subjects who rehearsed mentally a sequence of foot movements for 5 days, demonstrated, significant improvement of their performance after 1500 mental repetitions (Jackson et al., 2003). Likewise, when learning a complex sequence of finger movements, subjects in another study practiced physically (PP) or mentally (MP) 2 h a day for 5 days to learn the task. After 5 days, while best results were found in the PP group, the MP group had significantly improved in comparison to a control group, indicating that MP was effective, but not as effective as PP (Pascual-Leone et al., 1995). However, after one 2-h physical training session, subjects in the MP group reached the same level of performance attained by those in the PP group who had 10 h of physical practice. Thus, although the learning of a motor skill requires hundreds of repetitions, the number of physical repetitions to obtain similar gains can be less if subjects rehearse mentally prior to PP, indicating that MI can exert priming effects on subsequent PP. Similar priming effects have been observed in a study wherein subjects had to learn a precision grasp task. While it took 240 physical repetitions to learn the task, subjects who first did 120 mental rehearsals needed only 120 physical repetitions to reach an equivalent performance (Allami et al., 2008). These examples hint at the potential use of the priming effects of MI training in rehabilitation. For instance, the findings of Pascual-Leone et al. (1995) suggest that if only MI is used in the early rehabilitation phase when PP is not possible, (e.g., walking), then when PP becomes possible, less PP will be required to attain a given level of motor performance. Whereas, findings from Allami et al. (2008) suggest that when PP is possible, combining MP and PP will require less PP to attain a similar level of motor performance. These findings in healthy individuals also illustrate how the addition of MP to a rehabilitation program, should not necessarily entail an increase in the overall burden of therapy, but could in some cases simply imply a trade-off from one form of therapy to another.

MENTAL PRACTICE IN SPORT

Applications of MI training to neurological rehabilitation are also guided by findings in athletes who use imagery to practice motor skills and enhance skill acquisition or to facilitate the actual performance of a learned skill, as well as for motivation, self-confidence and anxiety reduction (Feltz and Landers, 1983; Janssen and Sheikh, 1994; Murphy, 1994; Rushall and Lippman, 1998; Guillot and Collet, 2008; Munzert and Lorey, 2013). Studies have clearly shown that the largest gains in motor performance are obtained when MP is combined with PP, and that MP alone yields better results than no training at all (Richardson, 1967a,b; Ryan and Simons, 1982; Feltz and Landers, 1983; Hall et al., 1990, 1992, 1998; Driskell et al., 1994; Brouziyne and Molinaro, 2005; Weinberg, 2008). MP is also used alone, without concomitant physical practice. For instance, prior to a competition it is used to refresh kinesthetic memory, especially for complex routines (gymnastics) or part of routines that are quite demanding physically, or between physical training sessions to maintain performance level (Rodgers et al., 1991; Murphy, 1994; Rushall and Lippman, 1998). For performance preparation, the focus is on factors that enhance performance such as motivation or activation (Paivio, 1985; Rushall and Lippman, 1998). Athletes imagine their forthcoming performance in real time to "get a feeling" for how to respond to the requirements of a task (Munzert and Lorey, 2013). Overall, athletes seem to use motor imagery more in conjunction with competition than with practice, perhaps because of its very important motivational function (Hall et al., 1990; Munroe et al., 2000; Munzert and Lorey, 2013). Several models of MP in sports (for a review see Guillot and Collet, 2008) include both a cognitive (learning) and a motivational (emotion) function; besides potential motor priming effects, athletes who imagine themselves performing well may become more motivated to practice harder and to compete more intensely.

RESEARCH PROTOCOLS IN NEUROLOGICAL REHABILITATION (TABLES 1 AND 2).

Given the large variety of research protocols that have been developed to examine the impact of MP, a classification of the types of protocols was made based on common characteristics. An important aspect that has surprisingly not often been systematically reviewed is whether MP is provided alone or in combination with physical practice. Next is the manner in which MP is provided: through audiotapes or guided by a therapist (one to one). It is also important to consider when MP is combined with PP, if it is within the same training session or a few hours apart in separate sessions. Thus, three modes of MI delivery have been proposed based on the analysis of the research protocols of 27 clinical studies in persons with stroke ($n = 25$) or with Parkinson's disease ($n = 2$) (**Table 1**). This classification is arbitrary, but reflects the reality of how MP is used in clinical practice. The first two modes (1 and 2) include protocols wherein MP and PP are combined, whereas, the third mode includes protocols with only MI training without specific physical training (mode 3). When mental and physical practice are combined, they are either carried out in separate sessions (mode 1: separate sessions) through different approaches (audiotapes: 1A or one to one: 1B) or provided in the same session (mode 2: concurrent session) under the guidance of a therapist with series of physical repetitions alternating with mental repetitions (**Table 1**). A first step in the analysis was to examine the type of tasks trained (ADL using the upper limbs or mobility and locomotor) across the three modes of MI delivery. **Table 2**, shows that 77% (21/27) combined physical and mental training (modes 1 and 2) and only six out of the 27 studies used MI alone (mode 3) and this allocation was similar whether training ADL (12/16: 75%) or mobility and gait (9/11: 82%). However, 56% of the MI studies of ADL tasks opted for audiotape delivery (mode 1A). This mode, however, was never used for training mobility and gait, instead, guided MI (one to one) was used in separate sessions (mode 1B: 36%) or with MP and PP provided in the same session (mode 2: 46%).

Another observation is that 74% of the studies (20/27) included patients more than 6 months post-stroke (chronic phase) after they had completed formal rehabilitation (**Table 2**). At such a stage, motor improvement is unlikely to be associated with spontaneous neurological recovery and thus functional improvement can be more readily attributed to a given intervention. The remaining studies were carried out with patients in the subacute phase post-stroke and all targeted ADL training with the upper limbs (Crosbie et al., 2004; Müller et al., 2007; Bovend'Eerdt et al., 2010; Riccio et al., 2010; Ietswaart et al., 2011; Braun et al., 2012; Timmermans et al., 2013).

Because MP is an adjunct to PP, it is hypothesized that patients receiving MP in addition to PP will demonstrate larger gains compared to a control group receiving only PP. In most controlled studies, a placebo intervention equivalent in time to the MP is provided to the control group to make up for extra contact time. To control for attention, the placebo usually consists of mental activities unrelated to movement imagery and can be delivered on tape (relaxation exercises; information about stroke, puzzles, etc.) or by audiovisual means (video, computer program, pictures, TV programs, etc.) with a content unrelated to the tasks practiced. This control for contact-time is not always provided (Page et al., 2009; Riccio et al., 2010; Lee et al., 2011; Cho et al., 2013) or the sham intervention consists of additional PP (Braun et al., 2012; Timmermans et al., 2013).

THE THREE MODES OF MI DELIVERY

SEPARATE MODE OF MI DELIVERY (MODE 1A AND 1B)

In mode 1 (**Table 1**), the MP and PP are provided in separate sessions with MI training delivered either through audiotaped scripts (mode 1A) or guided by a therapist on a one to one basis (mode 1B). The MI training is provided later in the day (Page, 2000; Page et al., 2001, 2005, 2007, 2009, 2011; Riccio et al., 2010) or right after physical and/or occupational therapy training sessions (Yoo and Chung, 2006; Bovend'Eerdt et al., 2010; Hwang et al., 2010; Lee et al., 2011; Nilsen et al., 2012; Cho et al., 2013).

MI Training of upper limb ADL tasks (Table 3: mode 1A)

In most studies involving upper limb ADL training, the MP was carried out in a quiet environment while patients lay supine or sat and listened to an audiotape describing the motor tasks to be rehearsed mentally (Page, 2000; Page et al., 2001, 2005, 2007, 2009, 2011; Yoo et al., 2001; Riccio et al., 2010; Nilsen et al., 2012). Largely influenced by cognitive and sport psychology (Suinn, 1984, 1985; Paivio, 1985; Sordoni et al.,

Table 1 | Modes of MI delivery and examples of tasks.

Research protocols	Tasks
(1) PP AND MI PROVIDED IN SEPARATE SESSIONS SEPARATE MODE OF MI DELIVERY	
(1A) PP + MI (relaxation + audiotape)	ADL
(1B) PP + Guided MI (one to one)	Gait, ADL
(2) PP AND MI PROVIDED IN THE SAME SESSION CONCURRENT MODE OF MI DELIVERY	
Guided MI (one to one): ratio 1 PP:10 MP; 1PP:5MP	Rising-up from a chair/sitting down, reach/grasp; gait
(3) MI ALONE: MI	
Guided MI (one to one)	Gait, ADL, sequence of finger movements

Table 2 | Modes of MI delivery in the research protocols of the 27 clinical studies reviewed.

Research protocols	ADL				Research protocols	Mobility and gait			
	N	%	Chronic (*N*)	Non-chronic (*N*)		*N*	%	Chronic (*N*)	Non-chronic (*N*)
Mode 1A	9	56	8	1	Mode 1A	0	0	0	0
Mode 1B	1	6	0	1	Mode 1B	4	36	4	0
Mode 2	2	13	0	2	Mode 2	5	46	5	0
Mode 3	4	25	1	3	Mode 3	2	18	2	0
Total	16	100	9	7	Total	11	100	11	0

2000; Cupal and Brewer, 2001), an audiotaped MI training session typically consists of a period of relaxation (3–5 min) wherein the patients are asked to imagine themselves in a warm and relaxing place and to contract and relax muscles. This is followed by 10–20 min of suggestions for internal, cognitive polysensory (visual and kinesthetic cues) images related to using the affected arm in one of several functional tasks. The tape concludes with 3-5 min of refocusing into the room (as described in Page et al., studies). Therefore, about 6–10 min of each session is not devoted to mental rehearsal as such.

Although the rationale for using audiotape delivery has never been explicitly justified, it is likely inspired by Paivio (1985), who underlined the importance of an accurate representation of the skill to be practiced, and thus proposed that language was an efficient way of activating imagery content. Likewise, the addition of relaxation prior to MI training was added to heighten concentration, promote vividness of MI, as well as to enhance performance and attention (Hall and Erffmeyer, 1983; Suinn, 1984, 1985; Sordoni et al., 2000; Cupal and Brewer, 2001).

The time allotted to mental rehearsal itself can be as little as 5 out of 10 min (Page et al., 2001), 8 of 18 min (Nilsen et al., 2012), as much as 15–20 min of a 30 min session (Page et al., 2005, Page et al., 2007, 2009) or as much as 48 out of 60 min (Riccio et al., 2010). **Table 3** gives a general idea of the total number of hours dedicated to MP and PP. Because MI training sometimes includes other components (e.g., relaxation, refocusing, implicit imagery) it was decided to determine the proportion of time dedicated to mental rehearsal alone. Thus, in the mental practice section (5th column in the Table), when there are two numbers the first number estimates the total number of hours allotted to mental rehearsal, whereas, the second number gives the total number of hours for the whole MI training session (including relaxation, etc.). When comparing the total hours of PP (column 4) and MP (column 5) sections in **Table 3**, it is clear that more time is devoted to physical than mental practice; the proportions are schematized in **Figure 1**. Although these numbers provide a general estimate arrived at from the descriptions found in the methods of the published articles, they illustrate the large variability in MI training regimens across studies. In addition, these numbers do not include self-practice or unsupervised training activities, since generally no information was provided about the compliance. About 3–6 tasks are rehearsed mentally over the training period, except in one study that included as many as 12 tasks (Riccio et al., 2010).

As for the physical practice part, based on descriptions found in the published protocols, the physical training generally focused on ADL tasks rehearsed later in separate MI training sessions (Page et al., 2005, 2007, 2009, 2011; Nilsen et al., 2012). Patients in these studies who were at a chronic stage with stable motor functions engaged in physical training sessions that ranged from 30 to 60 min, 2–5 times a week, over 2–10 weeks for a total duration ranging from 6 to 45 h (median of 9 h). Training generally involved 3–5 tasks (**Table 3**: mode 1A).

Gait tasks (Table 4: mode 1B)

Although MI training of gait was also provided in a separate session after PP, it was not delivered through audiotaped scripts, but guided on a one to one basis by a therapist (Hwang et al., 2010; Lee et al., 2011; Deutsch et al., 2012; Cho et al., 2013). However, relaxation prior to MI training was also used before MI training (Hwang et al., 2010) or after (Cho et al., 2013). In the four studies on gait training (Yoo and Chung, 2006; Hwang et al., 2010; Lee et al., 2011; Cho et al., 2013), MI training followed physical training and technical support was also used to illustrate what should be imagined; for instance, patients watched videos to learn about walking or to identify their own gait problems (Hwang et al., 2010; Lee et al., 2011).

As for the physical training component, it consisted of treadmill training (Lee et al., 2011; Cho et al., 2013) for 30 min, 3 times a week for 6 weeks (total: 9 h). In another study (Hwang et al., 2010), 1 h of regular physical therapy was provided 5 days a week for 4 weeks (total: 20 h), but the amount of time dedicated to gait was not specified. These examples illustrate the marked variations in intensity of physical training (20 h over 4 weeks: 5 h/week, vs. 9 h over 6 weeks: 1.5 h/week) across studies. Thus, given such variation in both the intensity and the specificity of the physical training, the assumption is that the contribution of PP to the overall effects is also variable.

Multiple tasks (Table 3: mode 1B)

Recently, attempts have been made to integrate MI training into usual clinical rehabilitation programs without increasing the total time of therapy (Bovend'Eerdt et al., 2010). MI training was used in the training of multiple tasks (upper and lower limbs, locomotion, etc.) instead of concentrating on a few selected ADL or mobility tasks. However, given the compliance problems with the therapists, the total amount of MI training could only be estimated by the authors (about 6.5 h) and the amount of physical practice was not reported.

Table 3 | Characteristics of MI training studies for upper limb tasks.

[Res Prot]/Study	*N*	TSS	PP	Mental practice				Mean change scores				
			Hrs	Hrs	Eval	√	Tasks	ARAT	FMA	Jebsen(%)	AFT	Midx
[1A]Page, 2000	E:8 C:8	1.8 years	6 6	2–4	NO	NO	?	NA	7.8 4.7	NA	NA	NA
[1A]Yoo et al., 2001	E:3	2, 12–16 months	0	2	NO	NO	1	NA	NA	NA	NA	NA
[1A]Page et al., 2001	E:8 C:5	6–11 months	18 18	1.8–3	YES	NO	3	16.4 −1.4	13.8 2.9	NA	NA	NA
[1A]Page et al., 2005	E:6 C:5	2 years	6 6	4–6	NO	NO	3	10.7 4.6	NA	NA	NA	NA
[1A]Page et al., 2007	E:16 C:16	38 months 45 months	6 6	4–6	NO	NO	3	7.8 0.4	6.7 1.0	NA	NA	NA
[1A]Page et al., 2009	E:5 C:5	13–45 months	*15 *15	10–15 No sham	NO	NO	5	15.4 8.4	7.8 4.1	NA	NA	NA
[1A]Riccio et al., 2010 NC	E:18 C:18	2 months	45	12–15 No sham	NO	NO	12	NA	NA	NA	14.1 0.83	11.4 1.9
[1A]Page et al., 2011	E:8 E:6 E:7 C:8	36 months	15 15 15 15	5–10 15–20 25–30	NO	NO	5 5 5	2.8 1.7 1.8 0.2	2.7 4.0 5.3 2.2	NA	NA	NA
[1A]Nilsen et al., 2012	E:5 E:6 C:6	43 months 20 months 33 months	6 6 6	1.6–4 1.6–4	YES	YES	3	NA	9.6 10.6 3.8	33 42 −13	NA	NA
[1B]Bovend'Eerdt et al., 2010 NC	E:15 C:15	22 weeks 16 weeks	Usual therapy	6.5	NO	NO	ALL	4.8 4.3	NA	NA	NA	NA
[2]Crosbie et al., 2004 NC	E:14	10–42 days	^{E}28 rep	^{E}280 rep	NO	YES	1	NA	NA	NA	NA	^{E}41 10–60
[2]Braun et al., 2012 NC	E:18 C:18	4–6 weeks	Usual therapy	?	NO	NO	ALL	NA	NA	NA	NA	17 21
[3]Stevens and Stoykov, 2003	E:1 E:1	1, 2 years	0 0	12 12	NO	NO	2	NA	10 12	67 33	NA	NA
[3]Müller et al., 2007 NC	E:6 E:6 C:5	1 month	0 10 0	10 0 0	NO	YES	1	NA	NA	30 40 0	NA	NA
[3]Ietswaart et al., 2011 NC	E:39 C:31 C:31	82 days	Usual therapy	8–9	YES	NO	12–14	5.9 5.3 7.3	NA	NA	NA	NA
[3]Timmermans et al., 2013 NC	E:18 C:14	1 month	Usual therapy	15	YES	NO	6	NA	4.0 5.0	NA	NA	NA

*PP, physical practice; TSS, mean time since stroke; Hrs, hours; Eval, MI assessment; √, manipulation checks; Tasks, number of tasks rehearsed mentally; ARAT, Arm Research Assessment Test (Max: 57); FMA, Fugl-Meyer Assessment (motor upper extremity: max 66); AFT, Arm functional test (timed test); Jebsen, timed test; Midx, Motricity Index (Max:100); [Res Prot 1A, 1B, 2, 3], research protocols described in **Table 1**; NC, non-chronic strokes; ^{E}Estimated from text and figures; *45 h with a glove on sound hand: constraint induced therapy (CIT); No sham, no control for contact time; NA, not applicable; ?, unspecified.*

Table 4 | Characteristics of MI training studies for mobility and locomotor activities.

[Res Prot]/Study	*N*	TSS	PP	Mental practice				Mean change scores					
			Hrs	Hrs	Eval	√	Tasks	Gait speed cm/s	Limb L %	ABC 0–100	Berg 0–56	DGI 0–100	TUG (s)
[1B]Yoo and Chung, 2006	E	5 months	2.7	2.7	YES	NO	1	NA	15	NA	NA	NA	NA
Standing	E	23 months	2.0	2.0					17				
	E	8 months	1.5	1.5					21				
[1B]Hwang et al., 2010	E:13	24 months	20	6–10	YES	NO	1	7	NA	46	23	17	5
Gait	C:11	23 months	20					2		10	8	1	3
[1B] Lee et al., 2011	E:13	Chronic	9	5–9	NO	NO	1	16	NA	NA	NA	NA	NA
Gait	C:11		9	No sham				10					
[1B] Cho et al., 2013	E:15	45 months	9	6	NO	NO	1	14	NA	NA	NA	NA	8.3
Gait	C:13	46 months		No sham				9					1.6
[2]Malouin et al., 2004a Rising-up/sitting	E:12	Chronic	7 rep	35 rep	YES	YES	2	NA	16	NA	NA	NA	NA
[2]Malouin et al., 2009	E:5	2.4 years	100 rep	1100 rep	YES	YES	2	NA	18	NA	NA	NA	NA
Rising-up/sitting	C:4	3.5 years	100 rep	0 rep					−6				
	C:3	2.4 years	0 rep	0 rep					6				
[2] Deutsch et al., 2012 Gait	E:1	10 years	1	5	YES	YES		35		11	NA	NA	2
[3]Dunsky et al., 2008 Gait	E:17	9–108 months	0	3–4.5	NO	YES	1	15 (8–38)	NA	NA	NA	NA	NA
[3]Guttman et al., 2012 STS	E:13	7–55 months	?	2.8–4	YES	NO	1	NA	0	NA	NA	NA	NA
[2]Tamir et al., 2007 Mobillity	**E:11**	**Stage 1.5–3 Hoen and Yahr's stage**	**12**	**12**	**NO**	**NO**	**3**	**NA**	**NA**	**NA**	**NA**	**NA**	**2.5**
Parkinson D	**C:10**		**24**										**-0.5**
[2]Braun et al., 2011 Gait	**E:25**	***1.5–3 and <3 Hoen and Yahr's stage**	**5**	**6**	**NO**	**NO**	**?**	**3 and 20**	**NA**	**NA**	**NA**	**NA**	**1.5 and 1.3**
Parkinson D	**C:22**		**5**					**14 and 18**					**3.4 and 1.0**

*PP, physical practice; TSS, mean time since stroke; Hrs, hours; Eval, MI assessment; √, manipulation checks; Tasks, number of tasks rehearsed mentally; [Res Prot 1A,1B,2,3], research protocols described in **Table 1**; NC, non-chronic strokes; Limb L, percent of limb loading on the affected side; STS, sit-to-stand; Berg, Berg balance scale; DGI, dynamic gait index; ABC, Activities-specific balance confidence scale; TUG, Timed Up and Go test; NA, not applicable; No sham, no contact time control; rep, repetitions; *results from 2 analyses: patients in stages 1.5–3 and patients in stages 1.5–2; bold, studies in persons with Parkinson's disease; ?, unspecified.*

CONCURRENT MODE OF MI DELIVERY (MODE 2)

In other studies, mental and physical repetitions were provided in the same training session with series of physical repetitions alternating with the mental repetitions. The ratio of MP to PP is variable across studies, with the number of MP increasing progressively from 2MP:1PP up to 10MP: 1PP (Crosbie et al., 2004; Malouin et al., 2004a, 2009; Tamir et al., 2007; Deutsch et al., 2012).

The rationale behind this approach is to tap into the priming effects of MI on subsequent physical performance (Pascual-Leone et al., 1995) and to decrease the number of physical repetitions (Allami et al., 2008; Reiser et al., 2011). In addition, visual and kinesthetic information acquired during each physical repetition refreshes the movement memory of the motor task and assists in the accuracy and vividness of the mental images and sensations for the next series of mental repetitions (Crosbie et al., 2004; Malouin et al., 2004a,b, 2009). It was also found that the timing (functional equivalence) of the motor task being rehearsed mentally improved when mental repetitions alternated with physical repetitions, thus suggesting that the afferent information is helpful for consistent reproduction of the next imagined movement (Courtine et al., 2004). Since MI training with this mode of delivery involves a large number of repetitions (up to 100 mental repetitions for 10 physical repetitions/session), most studies focus on one task at a time (e.g., reaching for a cup, standing up) and progression is made by increasing the difficulty of the task (e.g., biomechanical constraints) in steps tailored to individual requirements. Moreover, with the latter approach the total number of repetitions rather than the duration of the sessions is the key factor. Overall, more mental than physical repetitions are provided (**Figure 1**) and several hundred repetitions are targeted (Crosbie et al., 2004; Malouin et al., 2009), to promote motor learning (Nudo et al., 1996) and enhance the effects of physical practice (Allami et al., 2008; Reiser et al., 2011). For example, when combined with about 1100 mental repetitions, improved motor performance of the sit-to-stand task was obtained (Malouin et al., 2009) with only 100 physical repetitions, well below the 450–600 physical repetitions needed to promote motor learning of the sit-to-stand task (Monger et al., 2002; Barreca et al., 2004).

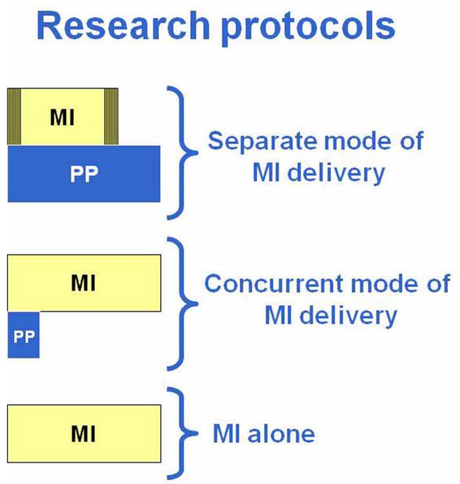

FIGURE 1 | Schematic representation of the time dedicated to Motor Imagery training (MI) and Physical Practice (PP) for each mode of MI delivery. The vertical lines indicate the proportion of time for relaxation (prior to MI) and refocusing (after MI). More time is allotted to PP than MI training in the separate mode of MI delivery, whereas in the other two modes more time is devoted to MI training.

Upper limb ADL tasks (Table 3: mode 2)

Only two studies combined MP and PP within the same session for the training of upper limb ADL tasks (Crosbie et al., 2004; Braun et al., 2012). In one study (Crosbie et al., 2004) that focused on the training of reaching and grasping movements, the proportion of MP to PP was 10MP: 1PP and overall the number of mental repetitions was estimated to be 280 (for 28 physical repetitions).

Gait and mobility tasks (Table 4: mode 2)

In studies using mental and physical repetitions for training mobility tasks in the same session (e.g., rising from a chair and sitting down), the ratio of MP to PP for training varied: 5MP: 1PP (Malouin et al., 2004a), 10MP: 1PP (Malouin et al., 2009) and 3MP: 3PP (Tamir et al., 2007). The total repetitions, over 12 training sessions with a ratio of 10MP: 1PP could be as much as 1100 mental repetitions and 100 physical repetitions (about 10 h of contact with the patient). In a recent case study (Deutsch et al., 2012), a ratio of 5MP: 1PP was used for gait training.

Multiple tasks (Table 3: mode 2)

The only study that used MI training for multiple tasks was carried out in a nursing home in patients with subacute stroke (Braun et al., 2012). Several tasks involving both the upper and lower extremities were trained. Given the problems with compliance, no information about the amount of training was reported.

MI ALONE (MODE 3)

While modes 1 and 2 of MI delivery also provide physical practice of the tasks rehearsed mentally, in mode 3, physical practice specific to the tasks rehearsed mentally was not included, and MI training was provided on a one to one basis. The rationale for using MI alone, as underlined in one study, was the need to show the benefit of MP alone to confirm its role in brain plasticity (Ietswaart et al., 2011). In reality, it is difficult to completely remove all physical training, especially in patients with subacute stroke who are engaged in usual rehabilitation programs (Müller et al., 2007; Ietswaart et al., 2011; Timmermans et al., 2013) or when MI training of gait is carried out in ambulatory patients (Dunsky et al., 2008) since one expects that the patients continue to be engaged in daily activities. However, one can assume that compared to the other studies that included intensive physical training specific to the tasks trained mentally, the amount of physical practice was likely much less.

Upper limb ADL tasks (Table 3: mode 3)

Some studies using MP alone focused on the learning of a finger movement sequence (Müller et al., 2007), wrist movements (Stevens and Stoykov, 2003), or upper limb ADL tasks

(Ietswaart et al., 2011; Timmermans et al., 2013). In these studies MI training was delivered under the guidance of a therapist or with a computer interface (Stevens and Stoykov, 2003) and the total amount of MI training was 10 (Müller et al., 2007) and 12 h (Stevens and Stoykov, 2003), respectively. Training generally involved 1–2 tasks, but in two recent studies (Ietswaart et al., 2011; Timmermans et al., 2013) carried out in the subacute phase, several tasks (6–14) were rehearsed mentally with training carried out on a one to one basis with the addition of an audiovisual (DVD) interface (Timmermans et al., 2013). In one study, MI training included mirror therapy and implicit motor imagery (Ietswaart et al., 2011).

Gait and mobility tasks (Table 4: mode 3)

MP alone for gait training was used by Dunsky et al. (2008). Guided by a therapist, the training included a relaxation period (2–3 min) followed by mental rehearsal of walking (10 min) and ended with a refocusing period (2 min). The MI training for the sit-to-stand task (Guttman et al., 2012) used a similar protocol, starting with relaxation and ending with a refocusing section.

In conclusion, the large diversity of protocols used to date reflects the search for an optimal approach. The rationale underlying the selection of a given protocol or training regimen is not always clearly defined. While the influence of former studies is at times clearly expressed, there is usually no justification for the selection of the intervention parameters.

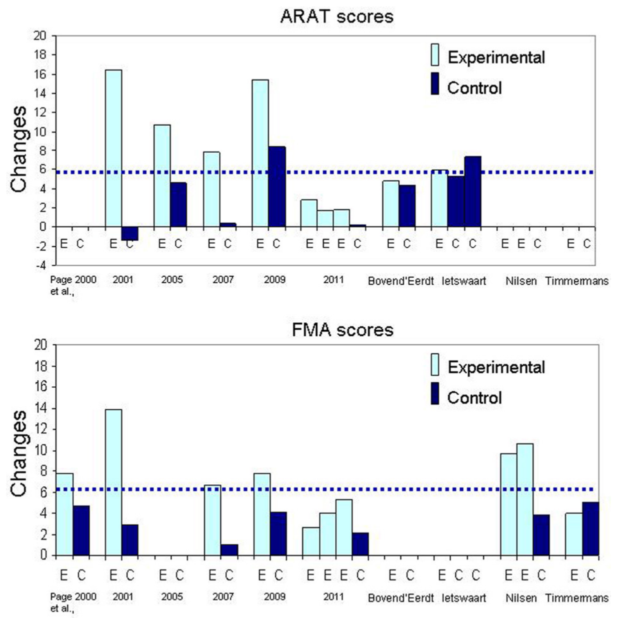

FIGURE 2 | Bar graphs illustrating the mean changes in Arm Research Action Test (ARAT) and Fugl-Meyer Assessment (FMA). The dotted line represents the Minimal Clinically Important Difference (MCID) for each outcome measure.

FACTORS INFLUENCING MI TRAINING OUTCOMES

ADHERENCE TO MI TRAINING

As reviewed above, there is much variability in the content of MI training and the time dedicated to mental rehearsal. Moreover, for most studies, it is impossible to estimate the number of mental repetitions over the training period (dose) since these are rarely counted. There is not only much variability in both the amount of time dedicated to MI training and in the mode of MI delivery, but one must also ponder whether the mental rehearsal was done correctly. Very few studies assessed the MI ability of participants (**Tables 3**, **4**), so there is no certainty that the patients were able to engage in motor imagery at the start of the study. In addition, even if they were good imagers, without manipulation checks to control whether they conformed to the instructions, it is impossible to confirm their adherence to the MI training. The findings that larger doses of MI training (**Figure 2**; comparison of 20, 40, and 60 min per session) delivered through audiotapes (Page et al., 2011) yielded inconsistent and not clinically meaningful results (very small ARAT gains and low trends of dose-related FMA gains) raise the question of patient adherence to instructions for the longer durations (e.g., mental fatigue, boredom) and further emphasize the need to control for patient compliance during MI training. Monitoring for compliance is especially important when patients are not interacting with a therapist or with external devices (e.g., computer-facilitated imagery) for 20–60 min while listening to taped instructions right after a relaxation period. The large differences between actual and mental movement durations found for ADL tasks routinely trained during audiotaped MI (Wu et al., 2010) further raises concerns to that effect. Patients with hemorrhagic strokes imagined the tasks 2–3 times faster than when they executed them physically (Wu et al., 2010), suggesting that they had difficulty in representing mentally complex tasks with accuracy (Guillot and Collet, 2005a). These findings, however, are at variance with those from diverse sources that observed some slowing (about 20–40%) of MI during hand pointing (Malouin et al., 2004c; Stinear et al., 2007) and stepping movements (Malouin et al., 2004c, 2012), especially after right hemispheric strokes (Malouin et al., 2004c, 2012; Stinear et al., 2007) or in patients with sensory deficits (Liepert et al., 2012). The large timing discrepancies reported by Wu et al. (2010) are worrisome and warrant the requirement of regular chronometric checks in future studies.

Although standardized audiotape delivery makes such manipulation checks more difficult, it can be done. Nilsen et al. (2012) conducted manipulation checks on the perspective used during mental rehearsal retrospectively, right after the end of the session. Asking patients periodically what they see or feel is also indicated to check whether the instructions are well-understood (Malouin et al., 2009; Deutsch et al., 2012). Since the enhancing effect of MI on cortical excitability and recruitment patterns depend on imagery quality (Lebon et al., 2012; van der Meulen et al., 2012), such debriefings to control the quality of imagery are particularly important. Their frequency can be reduced with time, as patients get more confident and experienced with MI. Dunsky et al. (2008) used chronometry of imagined walking to gauge engagement during imagery training; likewise chronometry was used during the MI training of rising from a chair and sitting down (Malouin et al., 2004a,b, 2009). It is thus recommended to plan for such MI manipulation checks, especially in older persons who have difficulty concentrating for long periods of time or with persons with impaired cognitive skills who can quickly lose track of ongoing tasks. To conclude, because imagery cannot be directly observed, manipulation checks should be mandatory to ascertain that patients imagine what they are instructed to imagine. Poor adherence could explain the moderate effects of MI training reported in a recent meta-analysis (Barclay-Goddard et al., 2011). The development of guidelines for optimal MI training starts with the control of factors such as MI compliance critical to the interpretation of the results.

THE CONTENT AND THE AMOUNT (DOSE) OF MI INTERVENTION

A frequent question about MP in neurological rehabilitation is how much practice (mental and physical) is necessary to promote learning effects? In this section, we try to relate MI training parameters to findings from studies using similar outcomes measures so as to derive indicators for success. In the majority of the studies with a separate mode of MI delivery for training ADL tasks, the same tasks were practiced both physically and mentally and the mental rehearsal part was delivered through audiotaped scripts (mode 1A) preceded by relaxation exercises (studies identified with 1A, first column in **Table 3**). In fact, spectacular effects (see **Figure 2**: change scores) were obtained with even less than 2 h of MI training, which corresponds to about 5 or 8 min of mental rehearsal per session (Page et al., 2001; Nilsen et al., 2012). Note also that with 4 h of MI training (Page et al., 2005, 2007) the outcomes were not better compared to those with 2 h (Page et al., 2001). However, for physical practice, the largest gains in ARAT and FMA scores were observed in studies with 18 and 15 h (**Figure 2**: Page et al., 2001, 2009) as opposed to 6 h (Page et al., 2005, 2007). The effect of more physical practice was also apparent even for patients in the control group when Constraint Induced Therapy (CIT) was provided to all (Page et al., 2009). Thus, the amount of physical practice appears to be determinant in the size of the effects observed when MP and PP are combined in separate sessions. In fact, based on the findings of the only study that examined the effects of different durations of MI training sessions, increasing the duration does not promote better outcomes (Page et al., 2011). This is not surprising since data in athletes suggest the optimal duration to be about 20 min and that a longer session may degrade motivation and increase negative effects such as boredom (Driskell et al., 1994). Likewise, beneficial effects of MI training (less bradykinesia) in patients with Parkinson's disease (**Figure 3**: lower graph) were obtained only for tasks practiced both mentally and physically (Tamir et al., 2007), further underlining the key role of PP when combined with MP. Thus, the addition of MI training to PP promotes motor performance of upper limb ADL and this performance is further enhanced with more physical practice, but not with more MI training.

These observations are in line with findings that when MI training was provided alone with usual therapy in patient in the subacute phase post-stroke, likely restricting the amount of PP of the tasks rehearsed mentally, it did not yield better outcomes than usual therapy despite very elaborate and intensive MI training (Ietswaart et al., 2011; Timmermans et al., 2013). In fact, when only one task was trained during MI training either with usual therapy (Müller et al., 2007) or when a large number of MP repetitions (mode 2) were combined with a small number of PP (Crosbie et al., 2004), significant gains were reported even at an early stage of recovery post-stroke. A possible explanation could be that when only one task is trained the higher intensity of MI training promotes better learning effects irrespective of the stage of motor recovery.

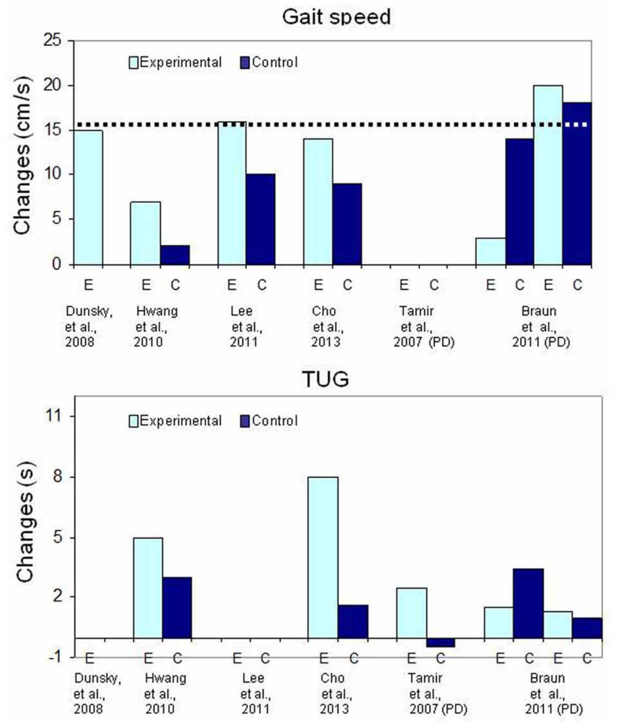

FIGURE 3 | Bar graph illustrating the mean changes (cm/s) in gait speed (upper graph) and the mean changes (in seconds) for the Timed Up and Go (TUG) test in patients with chronic stroke. The dotted line (upper graph) indicates the Minimal Clinically Important Difference.

For locomotor training, however, the addition of physical gait training does not seem to have such an impact on the magnitude of the outcomes (**Table 4** and **Figure 3**). For instance, a mean increase of 15 cm/s (range: 8–38 cm/s) was measured in patients after MI training of gait alone (Dunsky et al., 2008) and most of the gains in gait speed were retained at follow-up, 3 weeks after the end of training. On the other hand, despite 9 h of treadmill training (Lee et al., 2011; Cho et al., 2013), gait speed gains in the MI groups (14 cm/s and 16 cm/s, respectively) were similar to those reported by Dunsky et al. (2008) with MI training alone. In another controlled study, despite 20 h of physical training (unspecified exercises), smaller gains of 7 cm/s and 2 cm/s, corresponding to about half those reported in other studies were found in the MI and control groups, respectively (Hwang et al., 2010). Although the MI training group had gains that were statistically significantly larger compared to the control group, these changes in gait speed, were close to the standard error of the measure, which is 5 cm/s post-stroke (Perera et al., 2006). In addition, the 2 cm/s change in gait speed in the control group shows that physical training alone had no training effect, a rather surprising finding, especially in relatively young subjects (mean age: 46 and 48 years). A possible explanation for the small changes in gait speed after physical training could be related to the very intensive training regimen of 1 h of regular physical therapy and 30 min of MI training daily, 5 days a week for 4 weeks. Negative effects due to overtraining in inactive chronic patients might be responsible for this poor outcome (Sullivan et al., 2007). However, an important finding is that the small changes in gait speed in the MI training group were, however, associated with very large and clinically significant increases in secondary outcome measures such as balance (Berg scale), self-confidence (ABC scale), the Dynamic Gait Index (DGI) and Timed Up and Go (TUG) performance (e.g., Hwang et al., **Table 4**). The latter observations are surprising and lead one to question why these significant changes were not associated with larger increases in gait speed.

Thus, how much or what type of physical practice is needed? In studies without treadmill training, the effects of some physical practice cannot be discarded totally because the patients were ambulatory and thus continued to walk daily (Dunsky et al., 2006, 2008) and likely increased their walking activities (Cupal and Brewer, 2001; Page et al., 2005). Also, since these studies did not include a control group and that the amount of physical walking outside therapy sessions was not monitored, it is difficult to estimate the role of physical training in the reported gains. Nevertheless, the amount of physical gait practice was likely less compared to the intensive treadmill walking provided elsewhere (Lee et al., 2011; Cho et al., 2013). To conclude, for locomotor MI training, the addition of intensive specific treadmill training did not result in larger gains in gait speed, suggesting that in ambulatory patients, additional physical practice of locomotion is not essential.

The above analysis suggests that the interactions between MP and PP are not the same for upper limb and locomotor tasks. These interactions are schematized in **Figure 4**. The fact that more physical practice may be needed for upper limb ADL tasks is perhaps related to the greater level of motor skill associated with the control of upper limb movements compared to locomotor control which is a rhythmic and automatic activity that is also assisted by the sound leg in its expression.

Thus, it is very difficult to propose an ideal dose for MI training as positive results have been obtained with a variety of regimens. How many repetitions are required to obtain significant gains? Unfortunately, this is a question that has been overlooked so far in most studies examining the effects of MI in disabled populations. Moreover, because training intensity has been mostly reported in hours, we have little information to justify a recommendation for an optimal number of movement repetitions to provide clinically significant gains. We can, however, speculate that it is close to the number found to be successful in healthy persons who learned a new task after hundreds (about 1500) of mental repetitions (Jackson et al., 2003), or in persons with stroke who showed learning effects after about 1100 mental repetitions combined with 100 physical repetitions, for a ratio of 10MP:1PP (Malouin et al., 2009). Also, although no study has compared different ratios of MP: PP, learning effects have been reported with a variety of ratios: 10MP:1PP (Crosbie et al., 2004; Malouin et al., 2009); 3MP: 3PP (Tamir et al., 2007)

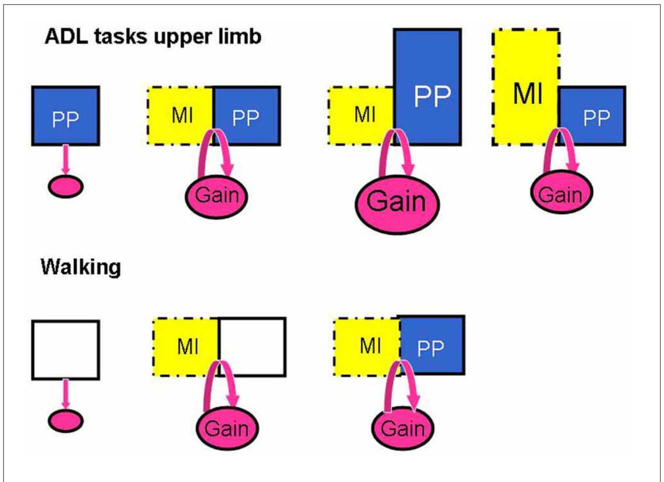

FIGURE 4 | Schema illustrating the patterns of responses when manipulating the amount of MI training and physical practice (PP) in the studies investigating the effects of MI interventions on ADL tasks of the upper limb and on walking. The addition of MI to PP promotes motor performance in ADL for the upper limb (Gain) and this performance is further enhanced with more PP, but not with longer MI sessions; for walking, however, MI alone promotes walking speed as much as MI plus treadmill walking.

or 5MP: 1PP (Deutsch et al., 2012). While in theory the more practice, the better, much like excessive physical practice can lead to muscular fatigue, too much mental practice could contribute to mental fatigue. This underlines the importance of monitoring both physical and mental fatigue in rehabilitation. More studies examining specifically dose-related effects of MP and PP will be necessary to gain a better understanding of these factors on motor re-learning following stroke. The gathering of such information is a key for future development of sound clinical guidelines.

RELAXATION COMPONENT IN MI TRAINING

Another factor that needs to be explored is the role of the relaxation component often included prior to MI rehearsal, particularly (but not only) in studies with audiotaped scripts (Page, 2000; Page et al., 2001, 2005, 2007, 2009, 2011; Yoo et al., 2001; Dunsky et al., 2008; Deutsch et al., 2012; Nilsen et al., 2012). What are the effects of adding relaxation on MI outcomes? During relaxation, patients are asked to imagine themselves in a warm and relaxing place (beach; bath) and to contract and relax their muscles (progressive relaxation) and in some cases they are asked to stay relaxed until the end of the session (Dunsky et al., 2008). In their study, Yoo et al. (2001) even used EMG recordings to confirm muscle relaxation. While relaxation is less applicable when physical repetitions alternate between series of mental repetitions, it has been almost automatically implemented with other modes of MI training to help the patients perform motor imagery. However, this notion has been challenged by many who state that relaxation is not essential and could even limit imagery-related benefits when used for improving motor learning and performance (Gray et al., 1984; Rushall and Lippman, 1998; Holmes and Collins, 2001). Some authors suggest that relaxation prior to MI training could be used as a starting point, but that it should not be maintained during the entire rehearsal session (Janssen and Sheikh, 1994). Relaxation may be indicated in stressed patients with difficulty imagining or those with poor concentration. Results from a recent study in healthy adults, however, revealed that imagery vividness did not differ in relaxed and aroused conditions (Louis et al., 2011). Moreover, when MI training was carried out in relaxed conditions, it seemed to alter the timing of MI, resulting in longer imagination than execution times (Louis et al., 2011). Some evidence suggests that the level of arousal should be close to that of the real performance (Holmes and Collins, 2001; Guillot and Collet, 2008). Furthermore, beneficial effects on motor performance and skill learning have been found with a novel approach combining real movement with MI, termed dynamic MI (Guillot et al., 2013), which is not compatible with any form of relaxation prior to MI.

In usual practice, listening to relaxation exercises on a prerecorded audio media has been considered as a neutral procedure and used in studies post-stroke as a sham intervention to control for contact time (Page et al., 2005, 2007, 2011; Nilsen et al., 2012). However, when relaxation has been used as a sham intervention in persons with Parkinson's disease, beneficial effects (**Table 4**, **Figure 3**) on walking performance (gait speed) similar to those observed in the experimental group following MI training have been reported (Braun et al., 2011). In the latter study, relaxation was provided in the same session as physical training. It is difficult to determine, however, how (e.g., reducing rigidity or increasing concentration) relaxation promoted a better motor performance in persons with Parkinson's disease. These results do suggest, however, that a relaxation-oriented MI intervention alone may be a factor to consider. Altogether these observations warrant a closer examination of the role of relaxation in the identification of optimal arousal conditions of future MI training rehabilitation protocols.

OUTCOME MEASURES FOR MI TRAINING

The selection of reliable and valid outcome measures is always a great challenge. It must take into consideration not only the reliability of a measure but also its validity and responsiveness. Of the many outcome measures available, the challenge is to choose a measure that is appropriate for the evaluation of the specific task that is targeted in the MI training. For instance, gait speed is recognized to be a very robust outcome for measuring the effects of training on walking (Wade, 1992; Richards et al., 1999). Also, because it is a continuous measure, it is possible to monitor progress over a large range of performance (Richards et al., 1995). Moreover, psychometric characteristics of gait speed are well-known, including its Minimal Clinically Important Difference (MCID: Tilson et al., 2010). The MCID is a useful means of evaluating whether the size of the gain in gait speed after an intervention is clinically meaningful, and it also allows for comparison of the effect across studies. For example, in one study, the statistically significant differences found in gait speed gains between groups suggested a better outcome in the MI group (Hwang et al., 2010). However, although there was a statistically significant difference between groups, the intense training regimen yielded small gait speed gains (7 cm/s) well-below the 16 cm/s MCID value (Tilson et al., 2010), and corresponding to about half the gains reported with other protocols of MI training for gait. On the other hand (**Table 4**: Hwang et al., 2010), gains in secondary outcome measures such as balance (Berg Balance Scale), movement quality (Dynamic Gait Index), obstacle walking and self-efficacy (ABC) measures were significantly larger in the MI group, signifying a role of MI training on the development of balance, self-efficacy, movement strategy and navigation skills which are important for developing walking competency (Salbach et al., 2004). Thus, secondary outcome measures can be helpful for the identification of collateral effects of MI training and to unveil positive findings despite small gains on selected primary outcomes.

The lack of statistical significance between two interventions, however, does not always mean that there are no training effects. For example, in a study involving persons with Parkinson's disease (Braun et al., 2011), no significant statistical differences were found in gait speed gains between a group trained with relaxation and another with MI, which led the authors to conclude that MI training had no effect. However, a closer inspection of the data (**Table 4**, **Figure 3**) reveals that both groups had gains in gait speed above the MCID, indicating that both interventions yielded gains that were clinically significant. This example further underlines the importance first, of selecting well-known outcome measures, and secondly, to examine the clinical relevance of the gains when psychometric properties are available.

Secondary outcomes can also further confirm the absence of MI training effects. This was the case in a study examining the effects of two modes of MI training on the learning of a complex mobility task: going down and getting up from the floor (Schuster et al., 2012a). The findings did not confirm that patients learned better when MI was provided in separate or concurrent sessions with physical training because the time to execute the task (outcome measure) diminished as much in the patients in the control group, who practiced the task physically during testing sessions, as in the two MI intervention groups. In addition, there were no significant changes either in the ABC scale or in the Berg Balance scale, further confirming the lack of MI training effects (Schuster et al., 2012a). Both the low intensity of MI training (less than 100 MI repetitions over a 2-week period) and the psychometric properties of the outcome measure (sensitivity and floor effect) could be responsible for the inconclusive findings.

The choice of an outcome measure such as movement speed is not always a valid or optimal measure and will vary according to the task to be evaluated and the aim of the training. For instance, if MI training is used to teach a new strategy (increase the amount of loading on the affected leg) during mobility tasks such as rising-up from a chair and sitting-down, the best marker of improvement is a gain in the amount of limb loading (vertical forces) on the affected side (Engardt et al., 1993; Cheng et al., 2001; Monger et al., 2002; Malouin et al., 2004a,b, 2009). In the early stage of training no change in the speed of movement is expected because it focuses on learning the motor strategy (Engardt et al., 1993; Carr and Shepherd, 1998), but after several weeks of training, improvement in both motor strategy and movement speed can be expected as the affected leg gets stronger (Engardt et al., 1993; Cheng et al., 2001; Monger et al., 2002). On the other hand, an increase in movement speed without a concomitant improvement in motor strategy signals a compensatory strategy with the sound leg (Engardt, 1994). Therefore, a gain in movement speed without an increase in limb loading on the affected side after MI training of sit-to-stand (Guttman et al., 2012) suggests that the MI training protocol did not promote the learning of the novel motor strategy. Likewise, the use of the knee extensor muscle activity (EMG alone) as an indicator of vertical force distribution between the paretic and non-paretic limbs as a means of assessing an improved motor strategy can be questioned (Oh et al., 2010), and requires prior validation.

The selection of outcome measures becomes even more complex when they are not specific to the tasks trained. For instance, in the RCT studies that evaluated the effects of MI training of several tasks, it is not clear how the ongoing recovery of the patients leading to, for example, increased muscle strength, better antagonist muscle coordination, or inter-segmental limb coordination, relate to the outcome scores from various tests using ordinal scales such as the Arm Research Action test (ARAT), Fugl-Meyer Assessment (FMA) or Motricity Index (MI). Although these clinical scales are very reliable (Lyle, 1981; Duncan et al., 1983; van der Lee et al., 2001; Lang et al., 2008), and provide a global score of performance, it is at times difficult to understand how they relate to specific changes in motor behavior. Examining ARAT subscales may, however, help pinpoint areas of improvement (e.g., pinch, grasp, or reach). Moreover, when impairment outcomes such as the FMA are used concurrently with quantitative measures such as those from the Jebsen test (Jebsen et al., 1969), they confirm a translation of training to motor performance (Müller et al., 2007; Nilsen et al., 2012).

When examining **Figure 2**, it is difficult to explain the modulation of the scores across studies sharing similar training protocols. For example, in a recent study (Page et al., 2011) MI training induced very small ARAT and FMA changes scores (not clinically meaningful) compared to those in previous studies (Page et al., 2001, 2005, 2007, 2009) despite similar MI training protocols. Another question concerns the relationship between the tasks rehearsed and the outcomes. Weight shifting exercises on the affected arm (Page, 2000) led to as much FMA gains as did tasks such as reaching and grasping, turning a page or writing (Page et al., 2007), further suggesting the non-specificity of such outcomes. Lastly, how can we explain so much variability in the ARAT change scores in control groups across studies (Page et al., 2001, 2005, 2007) and why are these changes so small despite 6–18 h of physical training (Page et al., 2001, 2007)? The small impact of usual therapy on patients in control groups (Riccio et al., 2010; **Table 3**) raises concerns about both the intensity of therapy (Lang et al., 2009) provided in early rehabilitation and the sensitivity of selected outcome measures (**Table 3** and **Figure 2**).

Few clinical studies have examined the specificity of MP training, by focusing on a single ADL task. The use of quantitative outcome measures such as a computerized test for assessing reaching times, the Box and Block test and the Purdue pegboard test might help gain a better understanding of the specific effects of MI on function. Crajé et al. (2010) showed that MI training of several functional activities could result in specific effects such as improved reaching and grasping but not of fine dexterity. Such findings are of interest because they help explain the specific MI training effects on motor function rather than having a global total score of grasping, reaching and pinching. Again, the psychometric properties of a test are useful to gauge the importance of the change not only statistically but also clinically. For instance, a gain of 7 blocks in persons with stroke on the Box and Block test translates to improvement of daily physical functioning (McEwen, 1995).

It is also important to assess generalization effects of MI on function. In a pilot study (Müller et al., 2007) the intensive MI training of sequential finger movements for 30 min per day, 5 days per week for 4 weeks, led to an increase in the peak torque of the pinch grip that was comparable to that obtained with physical training. Moreover, this increase in strength was generalized to better function of the upper extremity as measured by the timed items in the Jebsen test, (**Table 3**) that assesses the time taken to execute seven upper extremity tasks (Jebsen et al., 1969). Assessment of other outcomes such as concentration, motivation, or self-efficacy should also be considered because it is also important to evaluate the effects of MI on behavioral and cognitive functions (Hwang et al., 2010; Deutsch et al., 2012). Measuring the effects of MI on movement quality or on limb use with accelerometers (Timmermans et al., 2013) is also of interest because MI has been shown to lead to a spontaneous use of limbs trained with MI (Cupal and Brewer, 2001; Page et al., 2005).

To summarize, there is a need of studies that provide a clear link between MI training and specific parameters of motor function through quantitative and valid outcome measures to enable the development of evidence-based guidelines for MI training. In addition, secondary outcomes examining other components of behavior (motivation, self-efficacy, mood etc.) are useful because they extend our understanding of the mechanisms contributing to the positive effects of MI training.

GROUP HETEROGENEITY

In clinical studies, the comparability of patients from the intervention and control groups in a given study or among studies is critical to the interpretation of the results. For example, as illustrated in **Table 3** there is a large disparity in ARAT gains across studies. A possible explanation for this is the variability in patient level of activity limitations (baseline ARAT scores). For instance, in the study comparing the effects of Constraint Induced Therapy (CIT) with and without the addition of MI, which induced very large gains (Page et al., 2009), the standard deviation (SD) of the ARAT scores at baseline for both groups was very small (*SD* of 1.1 and 1.4, respectively) indicating that the 5 patients in each group had initially a similar level of activity limitation, and, as reflected by the SD of the mean change scores, they all improved in a similar manner indicating that all were good responders. In contrast, in the studies with larger patient groups at an earlier stage of recovery (Bovend'Eerdt et al., 2010; Ietswaart et al., 2011; Braun et al., 2012; Timmermans et al., 2013), the baseline ARAT scores had a large SD, indicating heterogeneity in the activity limitation level of the groups. Consequently, one can expect a variable response to training. Such variability in training response is well documented in studies providing individual data. For instance, in the Dunsky et al. (2008) study, although the mean gain in gait speed was 15 cm/s, the individual gains ranged from about 10 cm/s to 38 cm/s. The large *SD* of 15.66 for a mean gain of 16 cm/s in gait speed also reflects the large variability in individual responses to the same MI training (Lee et al., 2011). Likewise, in a series of case studies (Crosbie et al., 2004), individual gains extended over a wide range, also indicating that the group consisted of responders and non-responders.

The level of impairment also needs to be taken into consideration in data analysis and interpretation. As an example, in the Braun et al. study (2011) in persons with Parkinson's disease, larger effects of MI training were found in sub-groups of less impaired patients. Thus, additional comparisons between sub-groups of responders and non-responders can help tease out factors associated with the positive outcomes (e.g., sensory or cognitive deficit, level of motor impairment, anxiety, motor imagery ability, etc.). For instance, patients who learned to increase the loading on the affected leg during the rising-up from a chair and sitting down tasks were those with a good short term working memory (Malouin et al., 2004b). Correlative analyses between primary motor outcomes and secondary outcomes, such as anxiety and self-confidence, could serve as indicators on how MI is working (Cupal and Brewer, 2001). With analyses looking only at averaged data, important information about the type of patients most likely to benefit from MI training can be missed.

THE SELECTION OF PATIENTS

The selection of patients is another factor likely to influence the integration of MI training into clinical practice. The best example comes from a recent study that introduced MI training in the regular rehabilitation of older patients (mean age 78 years) who had suffered a recent stroke and lived in a nursing home (Braun et al., 2012). First, therapists found that teaching MI and assuring compliance of the patients proved difficult in these older and frail persons who needed long instruction periods that often induced frustration (Braun et al., 2010, 2012). In addition, it was not possible to implement the training without increasing therapy time, a downside often not acceptable within clinical settings. Also, older persons without previous exposure to MI appear to be less positive and less open to engage in these demanding and abstract procedures. Implementation of MI for the multitude of tasks practiced in regular therapy has also proven quite difficult with poor compliance by both younger (mean age 50 years) patients with stroke and therapists (Bovend'Eerdt et al., 2010). The poor compliance in these patients was explained in part by practical reasons (e.g., therapists on vacation), but it was also linked to patient-specific issues such as cognitive problems (Bovend'Eerdt et al., 2010). Although age as such is not necessarily a deterrent, the cognitive limitations associated with age and co-morbidities do contribute to poor compliance.

In fact, screening for cognitive problems and MI ability should be mandatory given the role of working memory in MI and documented working memory problems with aging and stroke (Malouin et al., 2004b, 2010, 2012; Schott, 2012). Both reduced working memory and poor attention skills can make the teaching of MI more difficult (Braun et al., 2010, 2012). Screening should also take into account language disorders that hamper the capacity to understand the instructions. It could also be that like other adjunct therapies, MI training may not be suitable or appealing to all patients because it requires first, to believe in the process, and then to accept to make the mental effort to engage in MI, a task that can be too demanding in some cases. Demands are also made on the therapists, who need to acquire some knowledge and understanding of the processes underlying MI training and then to develop expertise in its implementation prior to training patients. Such requirements may not be appealing or suitable to all.

Compliance to treatment requires the ability to imagine and it is surprising that MI ability is so rarely assessed (**Tables 3**, **4**). A possible reason is that because of its covert nature, MI needs to be assessed by different strategies. This has resulted in the development of several sophisticated approaches for assessing MI ability (see Guillot and Collet, 2005b; Heremans et al., 2008; Collet et al., 2011), that are not readily amenable to clinical settings when the therapist needs to decide whether a patient is able to engage in MI. Simpler and clinically amenable tests, however, are available. In our experience, screening can be done within a short time frame with an MI questionnaire and chronometric tests (Malouin et al., 2008a,b; Malouin and Richards, 2013). First, the administration of the KVIQ (Kinesthetic and Visual Imagery Questionnaire), informs on whether the patient is able to generate vivid images of simple movements (Malouin et al., 2007). Although, the questionnaire remains a subjective tool [e.g., such as a Visual Analogue Scale (VAS) for pain], the examiner can test whether the rating provided by the patient for a given item is genuine by asking the patient to provide details about the perspective (e.g., what part of the body is seen) and about the vividness of image (clarity, color etc.) and sensations (of joint, skin, muscles) perceived. Such a debriefing is important initially to make sure that MI instructions and scale ratings are understood correctly. Also, the pattern of responses can provide additional indices. If the patient always gives the same rating or always answers very quickly without concentrating, it suggests that more debriefing is needed. In other words, the administration procedures of the KVIQ, as well as the score provide some information about the ability of a person to engage in MI.

The MI questionnaire KVIQ was developed for testing persons with physical disabilities (Malouin et al., 2007) and it includes items that can be tested in sitting which makes this tool more accessible to persons with sensorimotor disturbances and balance limitations. The reliability and validity of the KVIQ have been documented in patients post stroke (Malouin et al., 2007, 2008b), in persons with Parkinson's disease (Randhawa et al., 2010) and a German version was recently validated (Schuster et al., 2012b). The validity of imagery questionnaires for assessing MI ability has been questioned because of the subjective nature of self-reported ratings (Lotze and Halsband, 2006; Sharma et al., 2006). However, over the last few years, studies examining brain activation patterns (fMRI and EEG) and corticospinal excitability (TMS) have found significant correlations between imagery scores and brain activity (Lorey et al., 2011; Williams et al., 2012; Vuckovic and Osuagwu, 2013). Note also that similar positive correlations have been described in persons with spinal cord injury (Alkadhi et al., 2005) and upper limb amputation (Lotze et al., 2001). However, MI vividness is a single dimension of MI ability and it is recommended from a clinical standpoint to use additional tests such as a chronometric test to further confirm the ability of a patient to engage in MI. For instance, comparisons between the duration of imagined and real movement (mental chronometry) indicate if the patient has a good temporal representation of the tasks being rehearsed mentally (see Malouin et al., 2008a; Malouin and Richards, 2013). Consequently, the first step to improve compliance to MI training should be to examine the MI ability of potential participants. However, because MI ability improves in the first weeks after stroke (de Vries et al., 2011), repeated evaluations are recommended before rejecting potential participants on this basis. As mentioned above, we need to develop criteria to guide the use of MI and the minimal requirement should be that patients be able to engage in MI.

MENTAL REHEARSAL: AUDIOTAPE SCRIPTS VERSUS A GUIDED ONE TO ONE APPROACH

Another factor that requires attention is the nature of MI instructions that differ greatly across studies. When MI training is carried out with audiotaped instructions, the patient listens to a script describing step by step how a task should be achieved (strategy), as well as the images and sensations during the completion of the task. Also, the wording can be very motivating, as it encourages patients to see the arm and hand moving freely and easily, and that the task is being performed effectively (Nilsen et al., 2012). Moreover, since the scripts are not always constructed to mimic movements in real time, participants are encouraged to repeat the movements at their own speed. For the task of drinking from a cup, participants, after being instructed to focus on reaching the cup, lifting the cup of the table and to bring it to the mouth, are then instructed to take a sip of water, then another sip and another sip and so on until they are feeling refreshed and are done drinking (D. Nilsen personal communication). This means that the number of repetitions can be quite variable from one patient to another and from day to day and suggests that the training strategy is not about reaching a certain number of repetitions. It seems rather, that patients gain some self-confidence in how the task should be performed (problem solving) and can be done successfully (motivation, reward), paving the way for the next physical practice session and suggesting that priming effects of MI take place *implicitly* during physical practice.

In contrast, in one to one guided MI, less emphasis is put on the emotional aspect, instead, the instructions are adapted to individual needs and limitations and more details *(explicit)* on how the movement should be performed are given. This is a very dynamic approach and requires a close interaction between the patient and the therapist who guides the patient throughout the stages of motor learning during both mental and/or physical rehearsals (Rushall and Lippman, 1998; Malouin et al., 2004a,b, 2009; Ietswaart et al., 2011; Deutsch et al., 2012; Timmermans et al., 2013). This mode is quite demanding for therapists who need time to introduce patients to MI training, a good knowledge about MI processes and prior familiarization with MI. Technical support is also used at times to illustrate what should be imagined. Mirror therapy (Ietswaart et al., 2011) or watching videos to learn about walking, or to identify their own gait problems from videos taken at different intervals (Hwang et al., 2010; Lee et al., 2011) and interacting with a computer and hardware devices for visual feedback of limb loading during a familiarization period in the first training session (Malouin et al., 2004a,b, 2009; Oh et al., 2010) are examples. It can involve actively imagining with the use of mirrors (Stevens and Stoykov, 2003; Ietswaart et al., 2011) or computer-facilitated imagery (Stevens and Stoykov, 2003). In addition, when mental and physical repetitions are combined within the same session, regular feedback about the physical performance is given by the therapist who also makes imagery checks with chronometry or some debriefing about the imagery to control for imagery quality (Crosbie et al., 2004; Malouin et al., 2004a,b, 2009; Deutsch et al., 2012). Thus, this approach likely puts a heavier demand on participant concentration and attention skills compared to audiotape delivery preceded by relaxation.

INTEGRATING MI TRAINING IN CURRENT PRACTICE: A FRAMEWORK

Although motor learning theories and neurological mechanisms are outside the scope of this review, one can speculate about how MI training can improve motor performance. Page et al. (2005) proposed that the motor improvement observed after MI training with audiotape scripts resulted from an increase in spontaneous motor activities. They found that patients after MI training used their affected limb more often suggesting that part of the gains observed could be attributed to the additional physical practice. Likewise, athletes after a rehabilitation program with MP for knee injuries demonstrated greater motivation to engage in physical therapy, which may have led to better rehabilitation outcomes. In the latter case, the subjects in the MP group had not only greater knee strength but this gain in strength was also associated with less re-injury anxiety than those in the control group, indicating that the MI training had effects on both psychological and physical rehabilitation outcomes and that reduction in re-injury anxiety and pain enabled the participants to relax and engage more fully in rehabilitation.

As demonstrated in animal models (e.g., Nudo et al., 1996) and in humans (Pascual-Leone et al., 1995; Lafleur et al., 2002; Jackson et al., 2003) the rehearsal of motor actions through physical and mental practice can induce brain changes (plasticity) associated with skill learning. As nicely demonstrated by Pascual-Leone et al. (1995), the changes in cortical sensorimotor maps after mental training are similar to those obtained with physical training. Since mental training has preparatory effects and increases the efficiency of subsequent physical training (Pascual-Leone et al., 1995) their combination is expected to yield best results. Although the optimal MI training approach remains unclear at this time, and that beneficial effects of MP on motor performance have been reported with all three modes of MI delivery, instead of using one exclusively, it might be reasonable to examine whether they could complement each other when used sequentially along the rehabilitation process.

Is the integration of MI training in rehabilitation programs a mission impossible? Based on previous studies, several features can hamper this integration: an early stage of motor recovery (e.g., implying spontaneous recovery), a wide spectrum of tasks, cognitive limitations, compliance with MI training, and relatively inexperienced therapists in the use of MP. Therefore, a first action would be to control factors that can be controlled such as: screening for impeding cognitive problems, assessing MI ability, determining an optimal number of tasks, training the therapists, planning for manipulation checks of MI and identifying valid primary and secondary outcome measures, while taking into account the advantages of each mode of MI administration along the rehabilitation continuum. The following strategy proposes a 3-step framework for the integration of MI intervention in current clinical practice (**Figure 5**).

STEP 1: INTRODUCTION TO MI TRAINING

Adding mental exercises to a training session that can sometimes be considered already too short can be viewed as too daring, especially if the patient is still a little confused and fatigues rapidly. So, at this stage, MI training should not be too demanding, both in terms of time and mental effort to learn the procedures. Therefore, to avoid removing time dedicated to regular therapy sessions, one might consider adding MI in a separate mode of administration with audio scripts (CD, MP3, etc.), audiovisual support, or web or stand-alone computer applications. This mode requires less professional resources once the scripts and the material are developed. At this stage, the aims would be to introduce MI, to familiarize the patient with MI, and to apply MI training to one or two tasks with scripts to learn the movement strategy and gain confidence for successful performance. The role of this MI training would be to prepare for the next rehabilitation training session when the same task is practiced physically to promote learning. This part of MI training would be the equivalent of performance preparation described in athletes prior to competition, and likewise the focus of training should be put on factors that enhance performance such as strategy, motivation and concentration (Paivio, 1985; Rushall and Lippman, 1998; Munzert and Lorey, 2013).

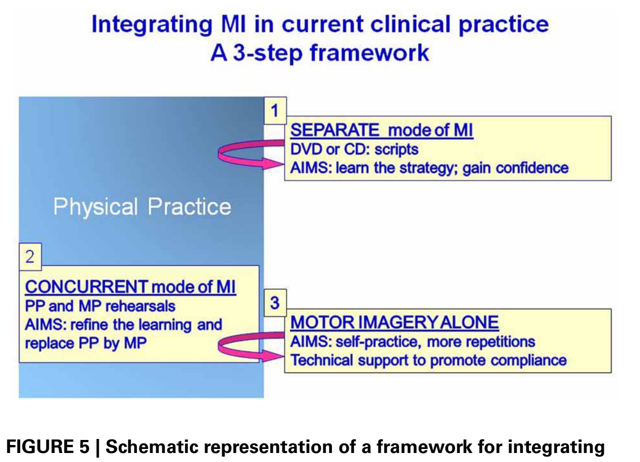

FIGURE 5 | Schematic representation of a framework for integrating MI training in current clinical practice.

STEP 2: INSERTION OF MI COMBINED WITH PP IN CURRENT TRAINING SESSIONS

Once the patient is well-familiarized with MI, the next step could then be to gradually introduce mental rehearsals of tasks that are also trained physically in regular training sessions (starting with a simple task and then increasing the number and complexity). This part relates to skill learning and the idea is to increase the number of repetitions through MI. It requires a close interaction with the therapist giving instructions adapted to individual needs and limitations (i.e., a more explicit approach). With the concurrent mode of MI intervention, feedback about physical performance is given by the therapist who also makes regular imagery checks to control for compliance and quality of MI. Because this approach is more demanding at the beginning, it is advised to start with a small number of mental repetitions and the ratio between mental and physical repetitions should be gauged according to individual capacities. This procedure has been integrated successfully into regular practice (Crosbie et al., 2004; Tamir et al., 2007). In one study, better outcomes were found in the persons with Parkinson's disease who had replaced half of the physical repetitions by mental repetitions (ratio of 3MP:3PP) indicating that the MI training group had larger gains despite less physical repetitions. The MI training targeted three tasks without increasing therapy session time. Furthermore, this approach proved particularly successful for the more physically demanding mobility tasks (Tamir et al., 2007). Likewise, at a ratio of 10MP to 1PP, training of reaching and grasping has also been successfully introduced into regular therapy without additional treatment time (Crosbie et al., 2004). At this stage the idea is to use mental rehearsal to promote the next physical execution of the task and the physical rehearsal provides sensory feedback to promote the vividness of the task rehearsed mentally.

STEP 3: SELF-PRACTICE FOR INCREASING THE NUMBER OF REPETITIONS

There is certainly a need to demystify MI training and to test its use in daily practice, but in small dose that focuses on a few tasks in a well selected patient population. However, since the basic ingredient of motor learning is the high number of repetitions (Pascual-Leone et al., 1995; Jackson et al., 2003; Allami et al., 2008; Reiser et al., 2011), we have to find ways of increasing the mental repetitions in a stimulating fashion outside formal therapy sessions. Homework are not very appealing to most and for those who try, it does not last very long (poor adherence). Thus, we need to develop dynamic interactive applications easy to use anywhere (i.e., electronic tablets) of computer-facilitated imagery (Stevens and Stoykov, 2003) to guide the patients through mental rehearsal routines of different levels of difficulty. This progression should include manipulation checks to control for imagery quality and compliance throughout each routine. This step is critical for developing some autonomy so that mental practice can be continued at home (Jackson et al., 2004).

FUTURE RESEARCH TARGETS

In the future, more effort should be put into clarifying the specific effects of MI training with each mode of MI delivery to determine their respective advantages and also to identify the characteristics of patients most likely to benefit from each type of delivery. We need to understand the role of factors such as the content and amount of training (physical and mental), relaxation, instructions and valid outcome measures (motor and behavioral). Motor learning theories in relation with the modes of MI delivery should also be examined. Because of the functional similarities between MI and motor execution, one would think that they share similar rules relative to motor learning, but recent findings in healthy adults have shown that while task variability promotes skill learning with physical practice, it does not have the same effect with mental practice (Coelho et al., 2012).

Much can be learned from the work accomplished to date, but prior to initiating large multicenter RCTs, so demanding both financially and in human resources, well-designed and hypothesis-driven pilot studies are also needed to clarify the impact of the many factors that influence MI training outcomes. For example, in one study with 14 patients, tested on 4 consecutive days, it was possible to compare the effects of four imagery protocols for MI training of walking (Kim et al., 2011). The findings of such studies contribute to the refining of future experimental paradigms in RCTs (Dobkin, 2009). For patients with difficulty in engaging in MI, the enhancing effects of brain stimulation, such as Transcranial Direct Current Stimulation (Ang et al., 2012; Foerster et al., 2013) or peripheral stimulation (Saito et al., 2013), on MI may prove to be useful. We also need to examine more closely the brain changes associated with MI training and also to characterize the effects of different modes of MI delivery using neuroimaging methodology such as Near Infrared Spectroscopy (NIRS) that is more amenable to recording changes in brain function during functional activities (Mihara et al., 2013).

CONCLUSION

This review delved into the details of research protocols using MI and uncovered several issues that should be addressed in future studies. The following points are important for future comparisons between studies, but also to facilitate the transfer of experimental findings to clinical settings. A better understanding is needed of factors contributing to training effects in relation to each mode of MI delivery, as is clarification of their respective impact at various stages (subacute-chronic) of motor recovery to guide their use. Thus, it is important to systematically record the content and quantity of training regimens (physical and mental) to gain some understanding of the dose-related responses associated with each mode of MI delivery. Also, it is essential to select patients that can engage in MI and to use manipulation checks to confirm their adherence to MI training. The selection of valid outcome measures specific to the trained tasks is a central issue; the choice of outcomes should be based on psychometric properties such as reliability and sensitivity to ensure detection of clinically significant changes. Finally, sub-group analyses are required to characterize responders from non-responders to a given MI training. This review proposes a framework to assist in the integration of MI into rehabilitation programs. We know little about the potential use of MP in persons with subacute stroke. Thus, the challenge has now shifted towards the demonstration that MI training can enhance the effects of regular therapy in persons with subacute stroke during the period of spontaneous recovery. The proposed framework is only a starting point. The combined effort of clinicians and researchers is essential to put it to the test, and to adjust it in accordance with ongoing clinical findings.

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Multiple roles of motor imagery during action observation

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Over the last 20 years, the topics of action observation (AO) and motor imagery (MI) have been largely studied in isolation from each other, despite the early integrative account by Jeannerod (1994, 2001). Recent neuroimaging studies demonstrate enhanced cortical activity when AO and MI are performed concurrently ("AO+MI"), compared to either AO or MI performed in isolation. These results indicate the potentially beneficial effects of AO+MI, and they also demonstrate that the underlying neurocognitive processes are partly shared. We separately review the evidence for MI and AO as forms of motor simulation, and present two quantitative literature analyses that indeed indicate rather little overlap between the two bodies of research. We then propose a spectrum of concurrent AO+MI states, from congruent AO+MI where the contents of AO and MI widely overlap, over coordinative AO+MI, where observed and imagined action are different but can be coordinated with each other, to cases of conflicting AO+MI. We believe that an integrative account of AO and MI is theoretically attractive, that it should generate novel experimental approaches, and that it can also stimulate a wide range of applications in sport, occupational therapy, and neurorehabilitation.

Keywords: motor simulation, mirror neurons, joint action, observational practice, mental practice, video therapy, occupational therapy, motor rehabilitation

INTRODUCTION

In this paper we contribute to the emerging integration of research on action observation (AO) and motor imagery (MI). We outline a coherent account of both forms of action representation, which have been typically studied in their own right and by different scientific communities and sub-communities (Moran et al., 2012). Our first point is not new: observers can engage in AO and MI simultaneously ("AO+MI"), and doing so does not take particular skill. Such integrated AO+MI appears to be more pervasive than either form of action representation alone. Our second and main point is that the contents of such simultaneous AO+MI need not coincide. We propose that there is a spectrum from fully congruent AO+MI, where the observer imagines performing the observed action, perhaps through periods of partial occlusion from sight and enriched by the imagined kinesthetic sensations that would arise during one's own motor execution, through to scenarios where the contents of AO and MI conflict, that is, where co-representation of two different actions is difficult or impossible to sustain and where markers of representational depth indicate competition. Lying between the extremes of congruent AO+MI and incongruent, conflicting contents of AO and MI is the co-representation of two different actions that can be coordinated in some manner. For example, in combat sports, I might watch a video recording of a future opponent whilst simultaneously imagining myself performing specific technical attacks or defense movements against that opponent. We believe that this proposed spectrum from congruent over coordinative to conflicting AO+MI states will motivate researchers to probe the two component processes, as well as their interaction, in greater depth than previously undertaken. At the same time, we can see tremendous opportunities for examining the application of various forms of concurrent AO+MI in motor learning and neurorehabilitation.

Our article is organized as follows: In the first section, we turn to the field of motor rehabilitation, where a number of research groups have already made a research-based case for combining AO and MI. Both forms of action representation have been proposed as promising adjunct treatments to conventional physiotherapy, but an integrated approach to treatment is still largely absent. We review recent neuroimaging studies which underpin the proposal of integrating AO and MI in motor rehabilitation and briefly point to future opportunities and open questions. In section "Action observation and motor imagery—a continuum," we outline an integrative account of AO and MI as motor simulation, inspired by the early contribution by Shepard (1984). In section "Motor imagery as motor simulation," we review the evidence, from both behavioral and neuroimaging studies, for MI as a prototypical form of action simulation, as originally proposed by Jeannerod (2001, 2006). In section "Research on action observation and motor imagery," we turn to research on AO, which has generated comparable evidence for motor simulation during AO. We then present evidence from two quantitative literature analyses for the rather scarce overlap between research on MI and on AO, and we discuss the links that have previously been made between the two forms of action representation. In section "Multiple roles of motor imagery during action observation," we then describe the full spectrum of AO+MI states as outlined above, along with possible training applications. On a theoretical level, we propose a distinction between a default mode of action simulation during AO and a more specific AO+MI state where the observer actively maps the observed action onto her/his own body schema via engaging in MI.

A CASE FOR MOTOR IMAGERY DURING ACTION OBSERVATION

In motor rehabilitation, both MI and AO have been proposed as adjunct treatments to conventional physiotherapy (e.g., Mulder, 2007; Garrison et al., 2010). The available clinical studies demonstrate varied success of both MI (e.g., Crosbie et al., 2004; Dijkerman et al., 2004; Page et al., 2007; Ietswaart et al., 2011; for review see Braun et al., 2013; Malouin et al., 2013, this issue) and AO therapy (Ertelt et al., 2007; Celnik et al., 2008; Ewan et al., 2010; Franceschini et al., 2010; Cowles et al., 2013; for review see Gatti et al., 2013), and a multi-center study on AO therapy is currently underway (Ertelt et al., 2012). Typically only one form of treatment, either MI or AO, has been used as an intervention [for an exception, see Ietswaart et al. (2011)], possibly with the conclusiveness of the clinical trial in mind. However, such a "purist" approach ignores the possible benefits of a multimodal motor simulation training with AO and MI as integrated components. For example, in some of our electrophysiological and neuroimaging studies, we have deliberately combined instructions for AO and MI in the practice phases (e.g., Wehner et al., 1984; Higuchi et al., 2012), with the aim of maximizing the benefits of non-physical forms of practice, even though doing so precluded specific conclusions about the effects of pure AO vs. pure MI vs. combined AO+MI.

Fortunately, a number of recent neuroimaging studies have directly contrasted these conditions using healthy participants. Filimon et al. (2007) compared activations during AO, MI (visuomotor imagery without visual input), and during execution of reaching movements, and they found differences between AO and MI only in occipital (visual motion) regions. Furthermore, motor execution induced stronger activations than either AO or MI in a number of execution-related areas, including primary sensorimotor areas, posterior parietal cortex, and dorsal premotor cortex [see also Vogt et al. (2007), for similar results during observation, preparation, and motor execution of a complex grasping task]. In no less than four recent neuroimaging studies, passive observation was contrasted with combined AO+MI, where the instructions required participants to imagine performing the displayed movement from a first-person perspective (Macuga and Frey, 2012; Nedelko et al., 2012; Berends et al., 2013; Villiger et al., 2013). Nedelko et al. (2012) designed their conditions to match their video therapy sessions with stroke patients and included videos of simple and multiphasic hand-object interactions, as well as pantomimed actions. Combined AO+MI induced stronger activations than passive AO in inferior parietal cortex, supplementary motor area (SMA), inferior frontal gyrus (IFG), caudate nucleus, and the cerebellum. Macuga and Frey (2012) contrasted passive AO, AO+MI, and AO plus imitative execution of bimanual finger sequences. In line with the results of Filimon et al. (2007), imitative execution induced stronger activations in a number of execution-related areas. More importantly, compared to passive AO, combined AO+MI increased activations in the pre-SMA and left IFG, as well as cingulate cortex and anterior insula. Further, a manipulation of visual perspective of the observed action (1st- vs. 3rd-person) only produced differences in occipital regions, which the authors attributed to differential stimulation of the lower and upper visual fields in their paradigm. In the fMRI study by Villiger et al. (2013), essentially the same three conditions as in Macuga and Frey (2012) were compared for first-person displays of a kicking action. MI during AO resulted in enhanced activations relative to AO alone in bilateral ventral premotor cortex, left inferior parietal cortex, and left insula. Further, a conjunction analysis of AO+MI and AO plus imitative execution showed a substantial overlap between the related activations in motor cortical areas, indicating that large parts of the motor execution network can be activated during AO+MI. Finally, Berends et al. (2013) demonstrated that the differences between combined AO+MI and AO alone can also be demonstrated using EEG. The authors found substantially larger desynchronizations during AO+MI, where participants observed movie clips of repeated pincer grips.

These studies highlight two important points. First, they strengthen the evidence for a considerable overlap between AO, AO+MI, and visually guided motor execution, in that all three forms of action representation involve a bilateral network within posterior parietal and frontal premotor cortex, also known as the "AO network" [see also meta-analysis by Caspers et al. (2010), and section "Research on action observation and motor imagery" below]. Second, AO+MI induced stronger activations in certain regions of this network than observation alone. On this basis, all four research teams recommended the use of combined AO+MI procedures in neurorehabilitation.

It should be noted, however, that stronger activations are not always "better," and that differential activations whilst engaging in action representation instructions do not allow direct inferences about the possible effects on skill learning. The study by Higuchi et al. (2012) illustrates this point: Participants were scanned during observational practice (involving combined AO+MI) and, in separate scanning sessions, during imitative execution of manual actions (guitar chords) that had previously been practiced either via AO combined with MI, or via physical practice. As expected, when scanned during AO, a common network involving posterior parietal and premotor regions was found activated, with only minor differences between the two forms of practice (see also Cross et al., 2009). During imitative execution, the results were strikingly different: Chords that had been observationally practiced induced substantially stronger activations during imitative execution than the physically practiced chords. Given that the behavioral data indicated smaller practice effects for the observationally practiced actions than for the physically practiced actions, and given the general trend for the cortical activations to reduce with increasing practice ("neural efficiency," Kelly and Garavan, 2005; Babiloni et al., 2009, 2010), these results indicated a lack of execution-related resources in observationally practiced actions. Importantly, however, when compared with non-practiced actions the observationally practiced actions also exhibited neural efficiency effects. Thus, whilst the study by Higuchi et al. (2012) reminds us that we cannot normally expect non-physical forms of practice to produce the same results as physical practice, it also indicates that AO+MI procedures can have substantial benefits. In future, it would be desirable that imaging studies contrast the practice effects of different forms of action representation, such as pure AO, pure MI, and AO+MI.

Taken together, the studies reviewed in this section not only illustrate the feasibility of simultaneous AO+MI instructions, they also demonstrate the immediate facilitatory effects of combining AO with MI, as well as longer-term positive effects on motor learning (sensu neural efficiency). Whilst further clinical trials are needed to confirm these effects in neurorehabilitation (Ertelt et al., 2012), the above studies clearly indicate that AO and MI training should not be seen as mutually exclusive means of treatment, but that their combined and simultaneous usage can be highly recommended. This conclusion will hopefully empower physiotherapists to develop and apply a wide range of tasks to help patients to (re-)engage in motor simulation processes. Many open questions remain at present, such as the suitability of specific subforms of motor simulation training for particular patient groups, the most suitable design of video therapy materials, and which perspective and modality instructions might be most appropriate.

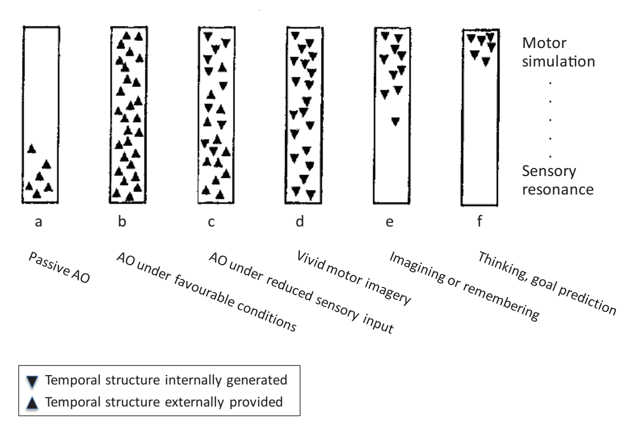

FIGURE 1 | The continuum between action observation and motor imagery, modified from Shepard (1984), for details see text. Note: Whereas Shepard's scheme encompassed a wider range of cognitive processes, we focus on AO and MI. In addition, we have replaced Shepard's ordinate of a "hierarchy of resonant modes" (from most concrete and sensory at the bottom to most abstract and conceptual at the top) by a sensory-motor axis.

ACTION OBSERVATION AND MOTOR IMAGERY—A CONTINUUM

Roger Shepard once caricatured "*perception as externally guided hallucination, and dreaming and hallucination as internally simulated perception*" (Shepard, 1984, p. 436). Similarly, we see AO as externally guided motor simulation, and MI as internally simulated execution. The idea that motor simulation might underlie both AO and MI was originally proposed by Jeannerod (1994, 2001, 2006), and more recently motor simulation, along with prediction as its most prominent cognitive function, has become a commonly accepted framework for a wide range of cognitive domains (Grush, 2004; Kilner et al., 2007; Bubic et al., 2010; Pezzulo et al., 2013). Before we turn to motor simulation in AO and MI in greater detail, we wish to illustrate the possible relationships between them by means of **Figure 1**, which is adapted from Shepard (1984) but reframed for the present purposes. Both schemata aim to distinguish different "*externally and internally instigated representational processes*" (ibid., p. 435).

ACTION OBSERVATION

With reference to **Figure 1**, the most frequently studied case of AO is (b), which represents observation of another person's action under favorable viewing conditions. The schema firstly suggests that this proceeds (rapidly) from sensory processing of the observed action to motor simulation processes (e.g., Eskenazi et al., 2009; Zentgraf et al., 2011; for discussion, see Kilner, 2011). Second, the orientation of the triangles indicates the externally driven character of sensory and motor processes in this case. This implies that motor simulation processes are not only initiated by sensory events but that they can also unfold in close coupling to external, temporally extended events such as observed actions. Rectangle (a) in **Figure 1** indicates that motor simulation processes are not mandatory in AO. For instance, in the domain of speech perception, Scott et al. (2009) concluded that motor simulation processes are more heavily involved under impoverished stimulation (e.g., distorted speech) so that (a) would represent the normal case in this domain. Whereas motor involvement in AO is a more typical finding than in speech perception, the latter at least illustrates the possibility of AO without the involvement of simulation processes. For instance, drawing on the study by Buccino et al. (2004), Rizzolatti and Sinigaglia (2010) conclude that "*these data indicate that the recognition of the motor behavior of others can rely on the mere processing of its visual aspects*" (ibid., p. 270; see also Gallese et al., 2011). Finally, rectangle (c) indicates that motor simulation during AO does not rely on continuous concurrent sensory guidance but can also proceed under reduced visual input, such as transient occlusion.

MOTOR IMAGERY[1]

Rectangles (d) to (f) represent wholly internally driven motor simulation. We propose that vivid MI can invoke the full spectrum of sensory and motor representation (d), whereas less vivid instances of MI, remembering, and goal prediction (e, f) might lack specific sensory features but still originate in motor simulation. In line with this, MI is commonly defined as the mental simulation of one's own performance without any associated overt movement (Jeannerod, 1994). It involves a subset of the neurocognitive preparatory and "real-time" processes of motor

[1]Note that in **Figure 1**, unlike in Shepard's (1984) original schematic, we have deliberately conflated the transition from perception (a–c) to imagery (d–f) with a change of the observer's viewpoint: for perception, we assume observation of a third person's action (the most typical situation in which mirror neurons have been studied), and for imagery, we assume MI of one's own action (first-person perspective). Already Jeannerod (1994) pointed to an intermediate simulation state, namely dynamic visual imagery of a third person's action, which comes closest to visual perception of another person's action. For simplicity of exposition we will largely neglect this case of external visual imagery in the present paper. However, we will consider perspective manipulations in AO in section "Perspective matters."

execution. More specifically, the preparatory phase of both motor execution and MI (Vogt, 1994) typically includes the anticipation of distal and proximal action effects (e.g., Ziessler et al., 2012) along with, for example, an action-oriented processing of object properties (Milner and Goodale, 2008). The real-time processes during both execution and MI further involve a "sense of effort" (James, 1890), agency (Frith, 2010, 2013), the experienced or simulated kinesthetic and other sensory input, and related monitoring operations (Shallice, 2004). One main difference between actual and imagined movement is that during the latter, motor commands are inhibited throughout the motor system to prevent overt execution (Guillot et al., 2012a). Practically, inhibition during MI may be a functional process resulting from the specific contribution of neural sites usually dedicated to overt motor processing. From a multifactorial viewpoint, motor inhibition might involve both cerebral and spinal mechanisms, and three possible routes for motor command inhibition during MI have been proposed in the literature (Guillot et al., 2012a).

In summary, **Figure 1** introduces the notion that AO and MI can involve a similar range of sensory and motor representational processes that constitute a continuous descriptive framework, where the two principal dimensions are the external vs. internal origin, and the emphasis on sensory resonance vs. motor simulation. AO and MI differ in that AO can involve motor simulation to varying degrees, and that it can rely on both external and (in part) internal guidance, whereas MI proceeds by definition in the absence of external guidance, and it can vary in the concreteness of sensory representation. These proposals will be elaborated in the next two sections.

MOTOR IMAGERY AS MOTOR SIMULATION

The ability to imagine is one of the most remarkable capacities of the mind to simulate sensations, actions and other types of experience. Morris et al. (2005, p.19) defined imagery as "*the creation or re-creation of an experience generated from memorial information involving quasi-sensorial, quasi-perceptual and quasi-affective characteristics, that is under the volitional control of the imagery, and which may occur in the absence of the real stimulus antecedents normally associated with the actual experience.*" Within this general definition, the process of imagining motor execution is known as MI. MI is a multimodal construct based on distinct sensory modalities, and there is compelling evidence that different imagery modalities and imagery types can be performed, with visual and kinesthetic imagery being probably the most frequently reported. Diary imagery studies have shown that about two thirds of our mental images are visual in nature (Moran, 2002). During internal visual imagery (first-person perspective), people visualize the action as it would happen in real-life and see images as if through their own eyes. During external visual imagery (third-person perspective), people imagine, like spectators, the action that somebody is performing, regardless of the agency of that movement (i.e., whether they "see" themselves or others performing it). By contrast, kinesthetic imagery involves the sensations of how it feels to perform an action, including the force and effort perceived during movement, hence suggesting the body as a generator of forces (Jeannerod, 1994). Practically, these definitions suggest that MI is *the* prototypical form of motor simulation (Jeannerod, 2001, 2006). While one can consider that pure visual imagery—i.e., without engaging in motor simulation—is possible (e.g., think about consequences of different actions abstractly), MI requires a motor strategy in almost all situations. In his motor simulation theory, Jeannerod (2006, p. 130) postulated that represented actions might involve a large subset of the mechanisms that usually participate in the various stages of action generation, including motor execution.

A significant number of experimental and neuroimaging studies support the proposal that MI involves motor simulation. First evidence comes from mental chronometry work, where researchers compared the time taken to imagine a movement with that needed to actually perform it (for review, see Guillot et al., 2012b). Since the pioneering contribution on this topic by Decety et al. (1989), a handful of experimental studies have shown that participants take the same time to achieve both physical and mental tasks. This is known as the principle of temporal congruence, which is based on motor prediction of the temporal features of the movement to be imagined. While there are several influencing factors likely to affect imagery times (Guillot and Collet, 2005), mental chronometry data strongly support that participants engage in motor simulation of the actual movement during MI by predicting as accurately as possible the temporal features of the corresponding action. A second line of evidence derives from recording the autonomic nervous system activity during MI. In their recent review, Collet et al. (2013) conclude that engaging in MI requires motor planning and programming operations, and anticipating the possible consequences of an action, such brain operations being accompanied by a set of physiological responses which can be recorded at the level of peripheral effectors. There is now ample evidence that MI and physical practice of the same movement elicit similar autonomic nervous system responses (e.g., Decety et al., 1991; Wuyam et al., 1995; Roure et al., 1999), and that imagery ability and efficacy can even be objectified and evaluated through autonomic responses (Collet et al., 2011).

Neuroimaging experiments also support the contention that MI involves motor simulation. Understanding the neural correlates of goal-directed action, whether executed or imagined, and exploring the neural underpinnings of different kinds of MI, has been an important purpose of cognitive brain research for the last three decades (for reviews, see Jeannerod, 1994; Grèzes and Decety, 2001; Nyberg et al., 2006; Munzert et al., 2009; Hétu et al., 2013). Briefly, studies have demonstrated that MI engages motor systems, and that the cerebral plasticity resulting from actual practice also occurred as a result of MI. These findings help to explain why MI can improve actual performance, and further contribute to motor memory consolidation. Of specific interest is the strong overlap between the neural networks mediating MI and the corresponding substrates activated during physical practice. Interestingly, Ehrsson et al. (2003) found that MI of hand, foot and tongue movements specifically activated the corresponding hand, foot and tongue sections of the primary motor cortex, hence suggesting specific motor simulation processes during MI. A similar conclusion can be drawn from studies comparing the neural networks activated during visual and kinesthetic imagery (Solodkin et al., 2004; Guillot et al., 2009), as motor systems were found to be more active during kinesthetic imagery, which is closer to actual practice and requires considering the body as a generator of forces to simulate the movement. Finally, a seminal clinical study in a patient with bilateral parietal lesions showed a complete unawareness of movement execution during imagery, where the patient exhibited hand movements during MI of the same body segments while explicitly denying that they occurred (Schwoebel et al., 2002). In other words, this patient engaged in complete motor simulation but failed to inhibit the motor consequences of MI which usually preclude actual movement.

A last line of (indirect) evidence of motor simulation during MI comes from experimental studies showing practice and instantaneous priming effects. Many studies of mental practice effects have demonstrated the efficacy of MI for improving motor performance and consolidation (for reviews, see Feltz and Landers, 1983; Driskell et al., 1994; Weinberg, 2008; Schuster et al., 2011). Such simulation of movements may engage relevant motor-related areas and might further build associations among processes implemented in different areas, hence facilitating subsequent motor execution (Jeannerod, 2001; Kosslyn, 2010). Recently, Ramsey et al. (2010) further demonstrated that imagining an action that was different to the to-be-performed action interfered with action execution. This finding shows that MI is likely to prime the motor system to produce the action, hence supporting that MI involves motor simulation processes (see also Vogt, 1995, 1996).

RESEARCH ON ACTION OBSERVATION AND MOTOR IMAGERY

While the general topic of mental imagery, if not MI itself, is one of the oldest areas of inquiry in psychology (Galton, 1883; James, 1890; Sully, 1892; Titchener, 1909), by contrast, "action observation" as a phrase seems not to have become prominent in the psychological literature until the 1990s, following a series of much-cited papers on mirror neurons and their properties (Di Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996, see Rizzolatti and Fabbri-Destro, 2010). Of course, this is not to say that observation of action was ignored by psychological research prior to this: it clearly was not. However, AO was given a new, or renewed, significance by the discovery of mirror neurons and developments in the understanding of perception-action links. Whereas the computational stages in MI, from the intention to act to real-time imagery, are most likely highly similar to those in non-imagined actions, the notion of direct links between AO and the motor system is less intuitive, and only over the last two decades, theorizing in neuroscience and psychology has fully embraced the latter idea. We now briefly recapitulate these developments, with a view on the commonalities and differences between AO and MI.

The discovery of mirror neurons in the macaque monkey was made in the context of *motor* neuroscience (Rizzolatti and Fabbri-Destro, 2010). The original findings opened up the possibility of establishing action understanding as a new, *cognitive* function of the motor system, and this pursuit has been a strong driver of the related research from its very beginning (Rizzolatti and Sinigaglia, 2010). Furthermore, once the existence of mirror neurons was established, for experimental scientists in various disciplines the study of AO and related imitative phenomena promised to illuminate intuitively appealing psychological topics such as empathy and theory of mind (but see Frith and Frith, 2006, 2012; Van Overwalle and Baetens, 2009). This prompted an impressive research effort into potentially similar mirror mechanisms in the human brain (Rizzolatti and Sinigaglia, 2010). Whereas the number of human brain regions with mirror properties and their exact functions is still under debate (e.g., Rizzolatti, 2005; Gallese et al., 2011), a large number of neuroimaging studies have demonstrated that motor cortical structures in the ventral and dorsal premotor cortex and in the adjacent caudal sector of the IFG are typically activated during AO, together with visual temporal and posterior parietal regions (Caspers et al., 2010), as well as somatosensory cortex (Keysers et al., 2010). Together these regions are also known as the "AO network."

As we have already noted in section "A case for motor imagery during action observation," a fairly large overlap of activations was found in the few studies that have directly compared AO and MI, possibly indicating that basic motor simulation processes are shared between MI and AO. Kilner (2011) recently proposed a two-process account of AO, where the initial action recognition (via a ventral temporo-frontal pathway) is segregated from motor simulation (via the parieto-frontal mirror circuit). This proposal does not preclude the rapid and simultaneous operation of the two processes, and it helps to clarify our present focus on the second process in Kilner's framework, motor simulation (Pezzulo et al., 2013). Motor simulation, in the sense of an internal, online representation of the observed action, is particularly useful when the observer needs to predict a certain temporal landmark (e.g., object release) of the observed action for purposes such as attuning one's own action toward this landmark or synchronizing one's own action with the observed action. A particularly impressive demonstration of the close coupling between observed actions and the observer's motor system was provided by Borroni et al. (2005), who showed that the excitability of the motor system exhibited a cyclical time course that closely matched that of an observed rhythmical action. In fact, such motor simulation, or "motor resonance" (Rizzolatti et al., 2002) is so universally useful that it might be described as a default mode of visuo-motor processing during AO. Finally, Schubotz (2007) and Bubic et al. (2010) have generalized this form of action prediction beyond actions that are in the behavioral repertoire of the observer and demonstrated that the premotor cortex is also involved in the prediction of non-biological events and event sequences. In summary, the available neuroimaging studies clearly support the notion of motor simulation as a default mode of AO, which can subserve a variety of functions.

In psychological research, the seminal reaction time studies by Brass et al. (2000) and Stürmer et al. (2000), both conducted in W. Prinz' perception-action group at the Max-Planck Institute for Psychological Research, motivated a large set of studies on visuomotor priming or "automatic imitation" (for reviews, see Vogt and Thomaschke, 2007; Heyes, 2011). Basically, these studies show that observed actions can bias the speed and accuracy in which similar actions are performed, and they thus provide behavioral evidence for direct links between AO and motor planning. A central feature of these studies is that the observed actions are normally irrelevant for the observer's own action planning, which strengthens the notion of low-level, automatic perception-action links. A second feature of this line of research was its focus on static depictions of actions [e.g., the prototypical lifted index finger of Brass et al. (2000)], although more recently automatic imitation effects have also been documented for temporally extended actions, such as everyday rhythmical actions (Eaves et al., 2012).

As already pointed out in section "Action observation and motor imagery—a continuum," a key difference between AO and MI is their external vs. internal origin. AO involves the sensory processing and attunement to the partly unpredictable action "out there," whereas these processes are by definition not part of MI. AO thus includes a wider range of neurocognitive processes than MI, particularly action recognition and intention understanding (Rizzolatti and Sinigaglia, 2010), action prediction (Springer et al., 2013), and collaborative action (either imitative or complementary, joint action, Bekkering et al., 2009). In the present paper, we focus on an instance of AO which exhibits the greatest similarity to MI, namely the repeated observation of largely predictable action displays, such as the repeated observation of object grasping as used in motor rehabilitation (Ertelt et al., 2007; Nedelko et al., 2012). As described above, a large number of both neuroimaging and behavioral studies confirm the involvement of motor processes in this form of AO. Notwithstanding the considerable overlap between AO and MI in this respect, AO surely encompasses additional neurocognitive processes.

This brief review of neuroimaging and behavioral research on AO reinforces the idea that, until now, the two bodies of research have not been particularly interested in the possible commonalities between AO and MI. Both neuroscientists and psychologists were (understandably) attracted by the opportunity to manipulate visual displays, rather than MI instructions, and to demonstrate visuomotor priming effects independently of the observer's task instructions. Likewise, researchers working on MI have rarely explored the virtues of using task-irrelevant displays, given that participants can be directly instructed to engage in MI tasks. That is, as already noted in the Introduction, until now the processes of AO and MI have, with a few notable exceptions, been considered separately and investigated by different groups of scientists[2] (for different sub-communities within research on MI, see Moran et al., 2012). In the remainder of this section, we present two quantitative literature analyses which tentatively support this claim, and then turn to previous points of contact and attempts of integration between the two research fields.

HIGHLIGHTS OF THE AO / MI LITERATURE

One way to demonstrate a lack of overlap between research on AO and MI is to revisit the related meta-analyses. Interestingly, the first such meta-analysis (Grèzes and Decety, 2001) encompassed motor execution and MI, as well as AO. The more recent meta-analyses, however, are either focused on AO (Caspers et al., 2010, on AO and imitation; Van Overwalle and Baetens, 2009; Grosbras et al., 2012, on AO and metalizing) or on MI (Hétu et al., 2012, 2013), but not on both. Despite the wholly legitimate, narrower focus of these recent meta-analyses, overlap between the underlying individual studies would still be conceivable. However, a comparison between Caspers et al.'s (2010) and Hétu et al.'s (2013) meta-analyses shows surprisingly little overlap: Of the 87 studies on cortical activations during AO and imitation that were included in the meta-analysis by Caspers et al. (2010), just four are also cited in Hétu et al.'s (2013) meta-analysis on the neural correlates of MI. Even allowing for different papers being reviewed in order to justify a novel contribution, this number is small. And of the 335 papers cited by the two articles together, just 18 are cited by both. This offers at least a prima facie case for claiming that the two research areas have not overlapped to the extent one might have expected.

Looking more widely at the impressive literature dealing with these two research areas confirms that MI and AO have been largely studied in relative isolation from each other. For instance, over the last 20 years, both MI and AO have been shown to contribute to improve motor performance and facilitate motor recovery, but few researchers have investigated whether MI and AO might be combined or considered in a common framework. We performed a literature search from the PubMed database by selecting indexed articles related to (*i*) motor/movement/action imagery and (*ii*) motor/movement/AO and action imitation. A large sample of 2172 references (including review papers) met the topical inclusion criteria (*note that a substantial number of sport-related references do not appear in the Pubmed database and were therefore not considered in this illustrative overview of MI and AO research areas. This may explain the unexpectedly small number of MI studies in Sport psychology*). 1203 articles investigated MI while 969 focused on AO. Each reference was then categorized as a study on either brain computer interface (BCI), cognitive psychology, rehabilitation, or sport psychology (**Figure 2**). The lack of AO research in BCI is basically expected and trivial. A larger number of AO studies than of MI studies was found in cognitive psychology, while the reverse was true in rehabilitation, which makes sense. The higher number of AO studies in sport psychology is more surprising, but the list of references retrieved from our chosen database is not exhaustive in this specific area.

The most important outcome of this analysis is that only 68 articles (3.1% of the sample) considered both AO and MI concurrently (including 14 review papers—2 in Cognitive psychology, 2 in Sport psychology and 10 in Rehabilitation). The most famous integrated accounts of AO and MI can be found in seminal theoretical papers (Shepard, 1984; Jeannerod, 1994, 2001, 2006; Annett, 1996). These authors specifically considered both the prescriptive nature and the neural models of action representations. Holmes and Calmels (2008, 2011) later contrasted the definitions and benefits of AO and MI. However, none of these important contributions was really designed to consider the possible role of MI during AO, either when AO and MI are congruent or incongruent. Few neuroimaging studies have considered both AO and MI, and the neural underpinnings of AO and MI were largely studied in isolation until more

[2]There are substantial critiques of the idea of scientific communities and of citation analyses as sufficient basis for establishing them (Woolgar, 1976; Edge, 1979; Knorr-Cetina, 1982; Zuckerman, 1987). Our aim is not to make a bold claim for the existence of separate (a problematic term) communities (another problematic term) but more modestly to highlight how the theories and findings have not been cross-referenced in a way we see as productive.

recently, when more detailed overviews of the substrates of action simulation have been provided (Munzert et al., 2009; Lorey et al., 2013a,b). Only a handful of researchers even considered concurrent AO+MI (see section "A case for motor imagery during action observation"). The advent of transcranial magnetic stimulation and the study of corticospinal excitability increased the number of studies contrasting and/or combining AO and MI (Clark et al., 2004; Leonard and Tremblay, 2007; Tremblay et al., 2008; Conson et al., 2009; Liepert and Neveling, 2009; Sakamoto et al., 2009; Battaglia et al., 2011; Feurra et al., 2011; Loporto et al., 2011; Bianco et al., 2012; Tsukazaki et al., 2012). Furthermore, researchers investigating BCI systems now consider the impact of both AO and MI on the modulation of brain rhythms (e.g., Neuper et al., 2009). Finally, some experimental studies in the field of sport psychology (Lejeune et al., 1994), cognitive psychology (Vogt, 1996; Conson et al., 2009; Ramsey et al., 2010; McCormick et al., 2012; Williams et al., 2012), as well as review studies in the field of motor rehabilitation (Mulder, 2007; Johansson, 2012) have investigated the respective effects of MI and AO and whether AO primes or improves MI [for a review on learning effects, see also Gatti et al. (2013)].

Basically, most of the studies mentioned above contrasted AO and MI, only very few considered concurrent AO+MI, and until recently, none had considered coordinative or conflicting AO+MI (see below). Curiously, several researchers opposed AO and MI in order to find which technique is likely to be optimal in enhancing performance. For instance, Holmes and Calmels (2008, 2011) stated that observation can provide some solutions to the problems identified in the use of imagery (e.g., image generation and maintenance, behavioral agency, control of visual perspective, and viewing angle) and offers a more ecologically valid environment for addressing many sporting tasks. Whilst this is probably sound in some circumstances and their examples are well-illustrated, it is unclear whether or not observation as conceptualized by Holmes and Calmels is accompanied by the mental representation of the corresponding action sensu MI. Another example comes from instructions delivered in some MI experiments where researchers have drawn conclusions about MI use when the participants were actually asked to engage in combined AO and MI (Macuga and Frey, 2012). All combinations

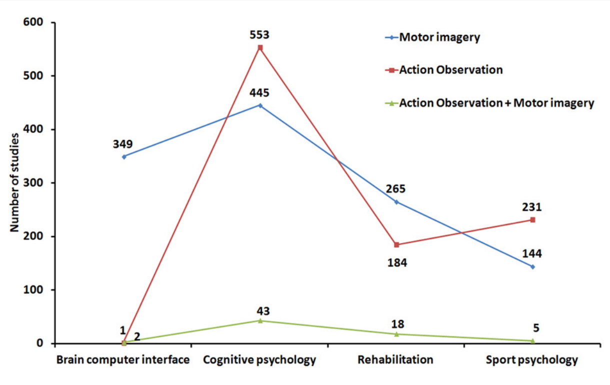

FIGURE 2 | Percentage of AO, MI, and AO+MI studies in the four pre-determined research areas.

of AO+MI procedures will now be detailed in section "Multiple roles of motor imagery during action observation," in order to provide a better overview of the possible associations and differences between AO and MI.

MULTIPLE ROLES OF MOTOR IMAGERY DURING ACTION OBSERVATION

In the previous section, we have pointed out that research on AO and MI has been carried out, to a large extent, by different research groups, despite the fact that integrative accounts of AO and MI as sub-forms of action representation, or action simulation, have been available for quite some time (Shepard, 1984; Jeannerod, 1994, 2001, 2006). The possibility of concurrent AO+MI states, however, was not featured in the above accounts. In section "A case for motor imagery during action observation" we have already made a case for concurrent AO+MI, based on the recent neuroimaging studies by Macuga and Frey (2012), Nedelko et al. (2012), and Berends et al. (2013). We now explore the full spectrum of AO+MI states (**Figure 3**), and begin with perhaps the most practically relevant scenario: the case of congruent AO+MI, which was also studied by the above authors.

CONGRUENT AO+MI

Here the observer is imagining self-execution whilst observing another person performing the same type of action. In a first approximation, the combined rectangles (b) and (d) in **Figure 1** correspond to this scenario, where rectangle (b) represents the simulation of the observed person's action, and rectangle (d) the simulation of one's own action. In line with our definition of MI, the latter simulation includes a "sense of effort" (James, 1890), a sense of agency, and the imagined kinesthetic sensations that would arise during one's own motor execution.

At first sight, the idea of two simulation processes that run in parallel might appear unparsimonious, but consideration of incongruent and conflicting AO+MI states (see below) will strengthen this "dual-simulation" view. Subjectively, the contrast between AO and AO+MI is striking: Whereas in typical AO, the observer can certainly engage with the observed action and, e.g., anticipate the next steps in a high jump or in a household routine, in concurrent AO+MI one's own body schema gets "switched on" and, e.g., an observed hand movement is mapped onto one's own felt hand (and in body-oriented actions such as brushing teeth, this simulation could further include imagery of the pressure of the toothbrush on the teeth). This subjective difference is presumably reflected in the stronger activations for AO+MI in a number of cortical sites found in the studies by Macuga and Frey (2012) and Nedelko et al. (2012). Further careful manipulation of imagery instructions during AO will be required to pinpoint the neural signatures of the two concurrent processes. For example, we would expect that activations in somatosensory cortex, which are consistently found during execution and AO (Keysers et al., 2010) would be substantially enhanced by related AO+MI instructions. Surprisingly, while this region has been found to be activated during MI (e.g., Porro et al., 1996; Lotze et al., 1999; Gerardin et al., 2000), the somatosensory cortex has rarely been considered a region of interest in MI studies, and, therefore, its involvement was not extensively discussed.

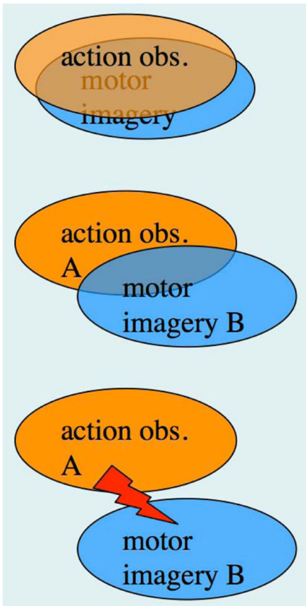

FIGURE 3 | The spectrum of concurrent AO+MI states. Top panel: congruent AO+MI; **Center panel:** coordinative AO+MI, where two different actions A and B are co-represented in some form; **Bottom panel:** conflicting AO+MI (see text for details).

The above conceptualization of AO+MI poses a number of important questions. First, it is unclear at present to what extent participants might carry out standard AO instructions as AO+MI tasks. That is, to what extent do they spontaneously imagine themselves performing the observed action, whether asked to do so or not. For example, in the prominent study by Calvo-Merino et al. (2005), observers were asked to judge "how tiring" the observed dancing movements felt,—an instruction that might well invite concurrent AO+MI. Accordingly, the frequency of spontaneous concurrent AO+MI is an important and largely ignored confound in the majority of existing neuroimaging studies on AO. The elegant fMRI study by Oosterhof et al. (2012) underlines this possibility via an in-depth comparison of activations for AO during motor execution with those for AO+MI.

Second, in our overview of different simulation states in section "Action observation and motor imagery—a continuum," we have left it open as to when the observer might hold a sense of agency. Generally we would assume agency for all forms of MI, including AO+MI. However, it is debatable whether the involvement of motor simulation processes during AO *per se* necessarily implies the sense of agency that is so typical of MI. As pointed out above, Schubotz (2007; see also Bubic et al., 2010) has argued that predictive operations of the motor system are not limited to human actions but include a variety of inanimate events. To give a recent example, Press et al. (2012) provided evidence for responses of the ventral premotor cortex, a classical "mirror" area, in coding geometric shapes. Thus, there are certainly examples of motor cortical involvement without experienced agency. Also for observation of human action, it is conceivable that motor simulation can occur without a sense of agency and without a mapping of the observed action onto the observer's own body schema. One possibility is that the observer only holds a sense of agency when he or she co-represents the observed action as their own action via MI. If this view can be substantiated, then the notion of "understanding actions from the inside" (e.g., Rizzolatti and Sinigaglia, 2010; Gallese et al., 2011) would appear to unnecessarily conflate "default mode" motor simulation processes during AO and the sense of agency that is experienced during MI and AO+MI. In other words, we suggest that the former processes do not imply agency, and that agency typically results from co-representation sensu AO+MI. The subjective experience of AO is not the same as that of AO+MI, and, despite the activation overlap documented so far, we would predict agency-related differences in the underlying neurocognitive processes.

A third interesting question arises regarding the nature of the interactions and temporal coupling between the observed action and the two proposed simulation processes. According to the single cell recording work on mirror neurons (Rizzolatti and Sinigaglia, 2010), the temporal coupling between the observed action and its internal motor representation is tight (see also Borroni et al., 2005). Indeed, these studies indicate minimal delays between the external event and its motor representation. In contrast, at present we have no information about the possible coupling between the observed action and the MI-related simulation, or about that between both internal simulation processes.

Fourth, it is entirely possible that engaging in MI concurrently with AO draws on resources that are normally used for simulation of the observed action. For example, performance in prediction tasks might be compromised, or perhaps even enhanced, by concurrent AO+MI instructions relative to AO instructions. Competition between these two simulation processes is even more likely in the following two scenarios.

COORDINATIVE AO+MI

Why should an observer imagine performing action A whilst observing a different action B? When the two actions have nothing in common, this is likely going to be difficult (see section "Conflicting AO+MI"). However, one could well argue that, in overt everyday interactions, performing one action whilst seeing another action done is even more common than imitative behavior. The former is currently studied under the heading of "joint action" (Bekkering et al., 2009), where one actor responds to an observed action with a different, self-performed action, normally in pursuit of a joint or competitive goal (see our example from combat sports in the Introduction). On closer inspection, also congruent actions almost always involve a certain degree of mismatch between observed and imagined action, for example regarding the plane of motion or perspective, or both. A further, prime example of joint action is ensemble music, where the very different actions of, e.g., a jazz singer and bass player are tightly coordinated in time (see Konvalinka et al., 2010). We would then argue that the capability to engage in incongruent AO+MI, where the two actions merit coordination in one way or another, is grounded in our capacity for joint action.

Compared to joint action, imagery in AO+MI widens the scope of possible scenarios considerably. During both congruent and coordinative AO+MI, observers normally focus their MI on selected aspects of the observed action. Indeed, the idea that all degrees of freedom of a complex observed movement could be mapped in a 1:1 fashion onto the observer's motor representation is plain nonsense from the point of view of sensory anatomy alone (Vogt, 2002). Rather, in the motor simulation of an observed action, the case of a purely sensorily driven simulation (rectangle b in **Figure 1**) is probably quite rare and limited to movements with very few degrees of freedom, such as isolated finger movements. In the majority of cases, however, AO will be focused on certain aspects of the observed action. Already in congruent AO+MI, it is clear that MI allows for a very narrow attentional focus, for example, on the left knee joint of an observed downhill skier and on the observer's corresponding joint. Finally, coordinative AO+MI is even more flexible. Returning to our jazz ensemble, the bassist might imagine tapping along with the singer in order to fully capture her intonation and timing. Or in our example from combat sports, the observer might visually focus on the opponent's right arm whilst, in different repeats of the video, focusing on different own body parts and on their optimal imagined response. In short, coordinative AO+MI is most likely a common everyday activity, and in formal training settings in sport or motor rehabilitation, it has an abundant range of applications.

CONFLICTING AO+MI

It is difficult to consider two actions, one observed and one imagined, that cannot be coordinated in some way but are solely conflicting. One example might be a skier observing a movie (showing either himself or someone else) of a slalom but simultaneously imagine himself falling during the same course, but this example might also be classified as a variant of coordinative AO+MI. In addition, and besides such (interesting) examples, it may be difficult to imagine a case of conflicting AO+MI which can be practically beneficial. However, the co-representation of conflicting instructions, task sets, or motor plans is of course a common research topic in psychology and neuroscience. For instance, most of the available research on automatic imitation effects (Heyes, 2011) relies on the contrast between compatible and incompatible visual stimuli during action planning as a methodological tool. We would thus like to illustrate possibilities for studying conflicting AO+MI, together with the other two AO+MI states, by means of an experimental paradigm that was recently developed in one of our labs (Eaves et al., 2012).

The starting point for the study by Eaves et al. (2012) was the relatively scarce evidence for automatic imitation effects in movement kinematics, as compared to the ample evidence from studies using reaction times. In each trial, participants were shown the picture of a rhythmical target action (e.g., toothbrushing), followed by a movie of an irrelevant distractor action (e.g., window wiping), followed by rhythmical execution of the target action. Across trials, the distractor action was presented in subtly different tempi, which produced a significant imitation bias during execution. In addition, the imitation bias was significantly stronger for congruent than for incongruent actions (where congruency could be regarding the type of action and/or the plane of motion). We interpreted these results in the context of Cisek and Kalaska's (2010) biased competition framework, where intended and observed actions can be represented as competing sensorimotor streams. For incongruent actions, we proposed that the competition between the two streams was strongly biased toward the intended action, and that, consequently, the coupling between the two streams was relatively weak.

A straightforward means of studying the three AO+MI states as proposed here would be to manipulate MI instructions during AO in the above paradigm. In a congruent AO+MI condition, participants could be asked to imagine performing the instructed action in synchrony with observing a congruent distractor action. Based on the results of the neuroimaging studies reviewed in section "A case for motor imagery during action observation," we would predict an enhanced imitation bias for this condition, relative to pure distractor observation as studied in Eaves et al. (2012). A coordinative AO+MI condition could be implemented by requiring participants to imagine the instructed action in synchrony with a distractor action that is incongruent in terms of action type or plane of motion. Whilst the studies by Hove et al. (2010) and Eaves et al. (2012) indicate stronger synchronization effects for congruent actions, it is also conceivable that explicit instructions to coordinate two different actions, as envisaged here, might produce a similarly strong imitation bias for such coordinative AO+MI as for congruent AO+MI. Finally, conflicting AO+MI conditions could be studied by asking participants to imagine holding a static posture of the instructed action during AO. Here we would expect that the imitation bias would be largely abolished. A second means of studying conflicting AO+MI would be to display a static image whilst participants imagine rhythmical performance of the instructed action. Such manipulations are suitable for exploring the relative strength of the biasing effects of AO and MI. Overall, we hope that this example has illustrated that the three AO+MI states, as proposed here, can indeed be subjected to detailed experimental investigation.

PERSPECTIVE MATTERS

As pointed out in Footnote 1, so far we have focused on third-person AO and first-person MI. Whilst a full discussion of all possible scenarios in the related 2 × 2 matrix would clearly exceed the scope of the present paper, here we briefly consider possible manipulations of visual perspective for AO only. In congruent AO+MI, observers can not only be presented with views of another person (third-person AO), but also with first-person displays that show the observer's limb(s) from a similar viewpoint as during execution. As described in section "A case for motor imagery during action observation," Macuga and Frey (2012) had manipulated viewpoint during AO+MI but these authors only obtained negligible differences—possibly due to the rhythmical task used. Interestingly, the recent clinical trial by Cowles et al. (2013) on AO treatment for stroke patients used a setup which approximated first-person AO, where the patients observed a model actor who was sitting next to them. Observation of a video in first-person perspective, indeed combined with MI, was also used as one of the treatment conditions in Ietswaart et al.'s (2011) study. Certainly, differences in visual perspective should not be ignored when trying to account for different outcomes of clinical trials, if only since viewpoint effects have certainly been found in behavioral studies (e.g., Vogt et al., 2003). A possible advantage of third-person visual displays during AO+MI is that the observer can keep the two representations related to AO and MI more easily distinct than two first-person representations. On the other hand, the latter might be more likely to induce a sense of ownership of the observed body parts, as shown in studies on the rubber hand illusion (Haggard and Tsakiris, 2005) and on mirror-box therapy (Altschuler et al., 1999; Kang et al., 2011). Surely more experimental studies and related clinical trials are needed before firm recommendations for presentation in first- or third person perspective, or perhaps for both, can be made.

For coordinative AO+MI, it appears unnatural to present the observed action in first-person perspective, since this would not match the typical scenario of joint action (see example in the Introduction). We would thus see first-person visual presentations in coordinative AO+MI to be of greater interest for experimental studies than for clinical or training applications. The same is possibly true for first-person presentations in conflicting AO+MI. For example, would the interference effects between the first-person MI and the conflicting visual displays as predicted in section "Conflicting AO+MI" be stronger for first- or third-person presentation of the distractor movies?

CONCLUDING REMARKS

The present paper marks the return of one of us (Stefan Vogt) to issues of MI after almost two decades abstaining from the topic, which has developed so healthily in the meantime. It is true that the field of AO *per se*, which has grown with at least the same rate over this period, offers ample opportunities to study perception-action relationships, and that MI is not a mandatory step to mediate perception and action (Vogt, 1995, 1996). Furthermore, it is likely to be more attractive for an experimentalist to manipulate visual displays instead of imagery instructions, which are always open to subjective interpretation (Holmes and Calmels, 2008). However, so are visual displays! We hope to have reminded researchers in the fields of AO and MI that the two processes do not only share, at least in part, the same neural substrate (although a meta-analysis of the now available evidence from both areas of research is currently lacking), but more importantly, that they are easily carried out simultaneously, most likely not only in the laboratory but also in everyday life. As we have described in section "Multiple roles of motor imagery during action observation," spontaneously performed AO+MI is an important and largely ignored confound in many related behavioral and neuroimaging studies. The act of "putting yourself into another person's shoes," or "action understanding from within" (Rizzolatti and Sinigaglia, 2010) might often involve processes of MI, albeit not necessarily in the sense of a deliberate conscious effort. With this we do not wish to question the possible contribution of motor processes to action understanding and action prediction in general. Rather, we wish to distinguish the latter from a more specific AO+MI state where the observer "switches on" his or her own body schema and actively seeks to align this with the observed action,—a process that is difficult to capture without reference to the concept of MI. We have described three subtypes of concurrent AO+MI, namely congruent, coordinative, and conflicting AO+MI, where particularly the first two bear the potential for a wide range of applications in sports, occupational training as well as neurorehabilitation. AO and MI are most likely highly intertwined processes, and their joint consideration is fruitful in theoretical and applied contexts alike.

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Using action observation to study superior motor performance: a pilot fMRI study

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The most efficient way to acquire motor skills may be through physical practice. Nevertheless, it has also been shown that action observation may improve motor performance. The aim of the present pilot study was to examine a potential action observation paradigm used to (1) capture the superior performance of expert athletes and (2) capture the underlying neural mechanisms of successful action observation in relation to task experience. We used functional magnetic resonance imaging to measure regional blood flow while presenting videos of a hockey player shooting a puck toward a hockey goal. The videos (a total of 120) where stopped at different time frames with different amount of information provided, creating a paradigm with three different levels of difficulty to decide the fate of a shot. Since this was only a pilot study, we first tested the paradigm behaviorally on six elite expert hockey players, five intermediate players, and six non-hockey playing controls. The results showed that expert hockey players were significantly ($p < 0.05$) more accurate on deciding the fate of the action compared to the others. Thus, it appears as if the paradigm can capture superior performance of expert athletes (aim 1). We then tested three of the hockey players and three of the controls on the same paradigm in the MRI scanner to investigate the underlying neural mechanisms of successful action anticipation. The imaging results showed that when expert hockey players observed and correctly anticipated situations, they recruited motor and temporal regions of the brain. Novices, on the other hand, relied on visual regions during observation and prefrontal regions during action decision. Thus, the results from the imaging data suggest that different networks of the brain are recruited depending on task experience (aim 2). In conclusion, depending on the level of motor skill of the observer, when correctly anticipating actions different neural systems will be recruited.

Keywords: motor representations, action observation, fMRI, expert performance, cognitive neuroscience

INTRODUCTION

The most efficient way to acquire motor skills may be through extensive motor training. Motor performance via motor skill training relies on the creation of internal motor representations, which enable us to repeat and, thereby, strengthen learned motor skills and improve performance (Dushanova and Donoghue, 2010). The motor representation comprises the entire movement, including the plan for the movement as well as the intended result (Kandel et al., 2000). Moreover, the motor representation is suggested to precede the execution, and could, therefore, be detached from the actual execution and exist on its own (Jeannerod, 2006). Interestingly, during action observation it has been suggested that the same neurons as are used during action performance are activated, which is referred to as the mirror neuron system (Rizolatti and Craighero, 2004). Further, it has also been shown that action observation may be used to enhance motor performance (Mattar and Gribble, 2005). Thus, if observing a movement also recruits the motor representation, then the representation itself may be strengthened, which may lead to performance improvements. In a related field to action observation, motor imagery, accessing the motor representation is also central. In this research field, studies have shown that task specific physical experience is needed in order to recruit motor regions of the brain during motor imagery, without such experience visual and pre-frontal regions of the brain will be recruited (see Olsson et al., 2008; Olsson and Nyberg, 2010, 2011). Similar suggestions have been reached within the observation literature. For example Calvo-Merino et al. (2005) showed that professional dancers could only recruit the mirror neuron regions of the brain when watching dance moves within their own motor repertoire. When observing dance like moves, other regions were recruited. Moreover, Aglioti et al. (2008) showed that expert basketball players used body cues to predict the fate of a basketball shot before the ball left the hand, which was also associated with a greater neural response in motor regions. Basketball coaches that no longer performed on expert level had to rely of the trajectory of the ball with less motor activity. In studies of action anticipation temporal occlusion paradigms have successfully been used to study points at which experts pick up the most information. For example, studies of anticipatory skills in badminton showed how experts are superior compared to novices in anticipating the landing position of strokes, which required fine tuned mechanisms in order to pick up information from the player's body kinematics early in the decision process (Abernethy and Zawi, 2007). Moreover, performance on temporal occlusion tasks are associated with expertise in the relevant sport, an advantage that is unchanged even if the stimulus material are changed from video clips to point-light information (Abernethy and Zawi, 2007). Further, the differences between experts and novices are even larger for the early occluded clips (e.g., Jackson et al., 2006). Thus, it is now widely recognized that experts pick up relevant information earlier than novices (see e.g., Abernethy et al., 2008). However, the neural underpinnings of such behavior are not completely understood. Wright et al. (2011) focused on differences between expert and novice badminton players. Their results showed that there appears to be overlapping regions between experts and novices while observing badminton videos, but it was also supported that novices tend to rely more on visual regions, and experts more on motor regions of the brain. Moreover, Bishop et al. (2013) suggested that high-skill anticipators showed a greater activation of mirror neuron related regions of the brain. Increased brain activity by experts was also supported by Wright et al. (2010), and Milton et al. (2007) proposed that the extensive practice over long time leading to expert performance is reflected by a focused and efficient organization of the neural networks related to a particular task. Thus, physical experience and motor representations appears to be important in order for action observation to be similar to action execution. However, there are still limited knowledge regarding the association between successful action anticipation, expertise, and neural response.

One reason why this is still uncertain may be that most of the studies have used passive control conditions. Hence, less attention has been given to examining what constitutes a successful anticipation, and, if such behavior relies on different neural systems between experts and novices. This is a novel step to analyze action observation by also include the performance of the observer into the analysis. This is important if we want to understand the possibilities of using action observation in practice and in order to provide guidelines in e.g., a clinical setting in which action observation is frequently used (Celnik et al., 2008).

The aim of this pilot study was therefore to examine if an action observation paradigm comparing expert athletes to novices could (1) capture the superior performance of expert athletes and (2) capture the underlying neural mechanisms of successful action observation in relation to skill level. We hypothesized that only the expert athletes could recruit motor regions of the brain and thereby access the motor representations when successfully anticipating actions. Moreover, we hypothesized that novices would recruit visual regions to a greater extent and use cognitive resources of the brain when successfully anticipating actions, which should be reflected by increased activity in pre-frontal cortex.

MATERIALS AND METHODS

PARTICIPANTS

For the behavioral part of this pilot, 17 male subjects participated voluntarily. Six of these participants were professional ice hockey players from the Swedish second division (experts, mean age 23.6 ± 4.1 years with 5.33 ± 4.5 years playing on professional level). Five of the participants were from the Swedish fifth division (amateurs, mean age 24.9 ± 2.6 years with 4.25 ± 3.6 years playing on amateur level). Finally, six of the participants had never played ice hockey regularly (novices, mean age 23.4 ± 1.8 years). The novices were students at the university with no hockey or team sport experience; neither did they attend games or sporting events regularly. Three participants from the expert group and three participants from the novice group also participated in the functional magnetic resonance imaging (fMRI) part of this pilot. No amateurs participated in the fMRI. All subjects participated voluntarily, reported right-handedness and were neurologically healthy. They all gave their informed consent and this study followed the ethical standards of the declaration of Helsinki.

STIMULUS MATERIAL

We decided to use ice hockey as the sport for our stimulus material because it allows one to capture different situations that are likely to appear as real game situations. Also, an extension of the present paradigm would be to look at more complex game situations with several players involved which would make hockey a good candidate in order to create more complex situations based on this initial pilot study. Moreover, there are several local teams available at different skill levels (from professional players to amateurs) making it ideal for us to be able to study skill differences. For the creation of stimulus material one ice hockey player from a Swedish ice hockey high school was used as a shooter and was given instructions how to perform the different shots. The video clips were recorded with a JVC Everio GZ-MG330HAG hard disk camcorder. The video camera was placed behind the goal. The position was chosen in order to be able to see the whole goal, as well as the shooter from the front, to facilitate the prediction of the puck direction. By using such a paradigm we will likely create a situation in which we will be able to compare functional brain response between experts and novices that will reflect differences based on their motor expertise. Since action perception and action execution has been suggested to recruit similar neural regions and also share a common representational domain (Prinz, 1997) we should thereby be able to study motor skill and motor representations.

The same stimulus material was used, and presented in a similar manner, both outside the scanner and during brain imaging. In total, 40 different video clips (10 clips for each location of the goal) of the shooting ice hockey player were used. Adobe Premier Pro CS4 was used to cut all clips into three different time occlusions to reflect the different levels of difficulty. First, all clips were cut when the puck left the stick (easy occlusion). Then, the same video was also cut 300 ms (medium occlusion) and 600 ms (difficult occlusion) before the puck left the stick. Each video clip was about 2 s long depending on which occlusion time that was used. Each video clip was shown three times with different occlusions each time, thus, the total amount of video clips was 120. Original resolution was 720 × 480 pixels (standard PAL video, 4:3 interlaced), but it was cropped to 416 × 480 pixels in order to remove unwanted information in the picture. E-Prime 2.0 was used to randomize the clips and to collect response data.

PROCEDURE

Before the start of the experiment the participants were given five trials of video clips that were not used in the actual test. The instruction for both the trials and the experiment was to watch each video clip as if they were the player. After each video clip the participants were asked where in the goal the puck would go, they responded by pressing a button. They had four alternatives; they pressed one if they thought that the puck would go to the furthest left, and four if they thought that the puck would go to the furthest right. They could use as much time as they needed to make their response. Then the participants were asked to respond to how confident they were of their answer. Again, they had four alternatives, pressing one if they guessed and four if they were 100% sure of their answer (see **Figure 1**). The same procedure was done in the behavioral part of this pilot as well as during fMRI scanning. During scanning the participants were placed in the scanner and watched a video screen via a tilted mirror on the head coil. They had a response pad under their right hand, attached with Velcro. The participants had earplugs and a headphone to reduce the noise from the scanner and cushions were placed in the coil to minimize head movements. They were also informed not to move any body parts during scanning.

BRAIN IMAGING PARAMETERS

The fMRI session was conducted on a GE3.0 T system (USA) collecting Blood oxygen level dependent T2* weighted images. The following imaging parameters were used: repetition time 2000 ms; 37 slices with a thickness of 3.4 mm, echo time 30.0 ms, flip angel 80°; field of view 25 cm × 25 cm, matrix 96 × 96. Before statistical analysis pre-processing steps were carried out using SPM5 (Wellcome Department of Cognitive Neurology, London, UK) including: slice timing correction, realignment, unwarping, normalization to an EPI template in the Montreal Neurological Institute space, and finally spatial smoothing (8 mm Gaussian filter). In-house developed software (DataZ) was used for visualization of the results.

STATISTICAL ANALYSIS

To capture performance the mean value of number of correct answers at each difficulty level (easy, medium and difficult occlusion time) was counted. Subjects' confidence on their answers was calculated as mean value on each difficult level. A 3 × 3 (3 skill levels × 3 difficulty levels) ANOVA was used to analyze behavioral data between groups. Least significant difference was used as a *Post-Hoc* test. Level of significance was set to $p < 0.05$.

Imaging data was analyzed in respect to observation as well as during decision-making, therefore these two conditions were defined as separate regressors. The observation regressor was based on the entire length of each video clip, whereas the decision regressor was the length up until the participants gave a response. Our main aim was to investigate prediction of the action outcome in relation to successful performance. Since previous studies have not contrasted successful trials vs. unsuccessful trials in their analyzes, we are still uncertain what constitutes successful action anticipation. Relying on passive control conditions, as has been done in prior studies, is a liberal approach in fMRI studies. In the present study the more conservative analytic approach motivates the use of a pilot study before testing the hypotheses in a large-scale attempt. Therefore, single subject contrasts were set up using the general linear model and statistical parametric maps were generated using t-statistics. The main contrast used was comparison of functional brain response during correct vs. incorrect (correct > incorrect) response. This was done for both the observation as well as the decision-making. We then performed a random-effect analysis for each group separately. We used a significant level of $p < 0.005$ uncorrected in the analysis. The voxel-wise threshold was motivated since this study should be considered as a pilot requiring more of a descriptive approach. However, in order to minimize Type I errors, a cluster threshold of minimum five voxels was also applied.

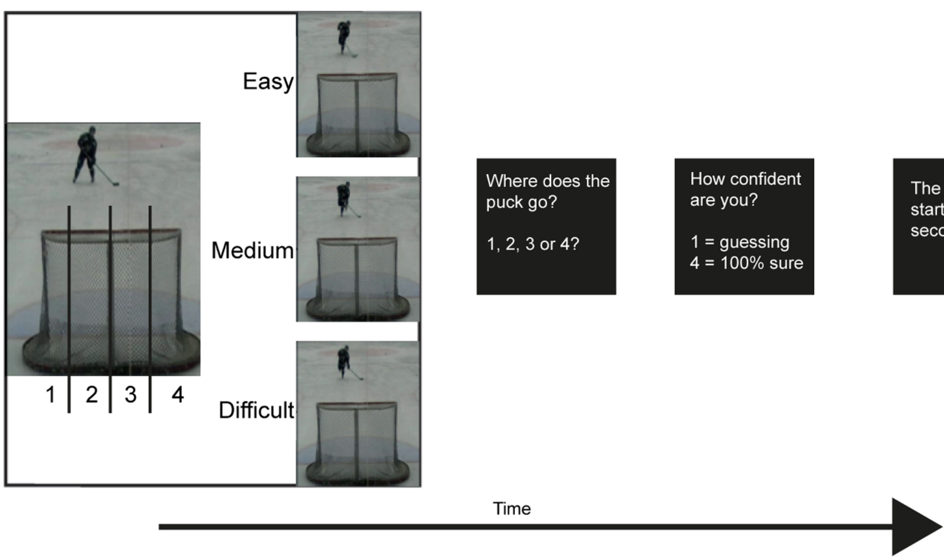

FIGURE 1 | Experimental setup. The video clips lasted for about 2 s depending on which occlusion (easy, medium, difficult) that was observed. There was no time limit for the response. The participants viewed a total of 120 video clips.

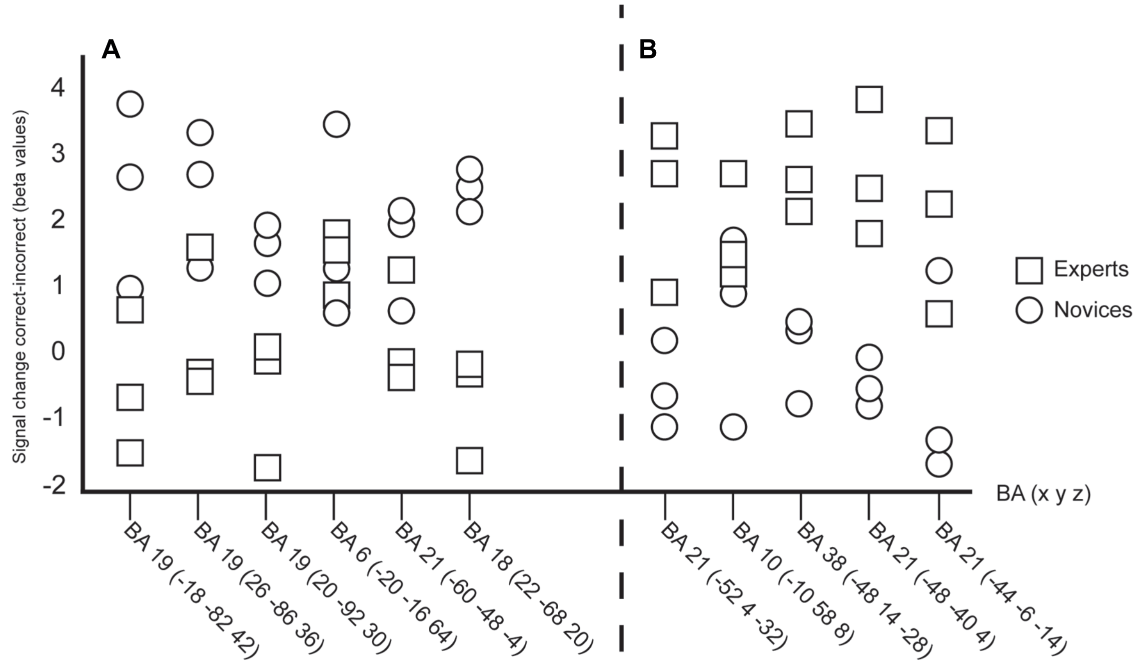

FIGURE 2 | (A) Individual plots of the local maxima revealed from the clusters by the novices (see **Table 1**) during observation of the early occluded clips. **(B)** Individual plots of the local maxima revealed from the clusters by the experts (see **Table 3**) during observation of the early occluded clips. The individual plots confirm that experts and novices are using separate neural networks during successful anticipation of actions.

RESULTS

BEHAVIORAL DATA

Between group analysis revealed significant difference in performance on easy level ($F_{2,14}$) = 3.739, $p < 0.05$ and difficult level ($F_{2,14}$) = 4.653, $p < 0.05$, effect sizes were small to moderate, $\eta^2 = 0.025$ and 0.045 respectively. There was a tendency to significant difference in performance on medium level, $p = 0.061$. *Post Hoc* test showed significant differences between experts and novices on both easy and difficult level $p < 0.05$ and also between amateurs and novices on difficult level $p < 0.05$. Both groups were equally confident in their responses.

fMRI DATA

Distinct differences in recruited brain regions were revealed between experts and novices both during action observation but also during action decision. The activation pattern for novices during observation (see **Table 1** for exact location in MNI-space, *T*-values, and cluster extent) was mainly associated with regions of the visual cortex, especially at the difficult occlusion. During action decision (**Figure 3**), regions of the pre-frontal cortex, such as middle, superior and inferior frontal cortex was mainly recruited (see **Table 2** for exact location in MNI-space, *T*-values, and cluster extent).

For experts, the activation pattern during action observation involved mainly regions in the superior and middle temporal gyri, but also the pre-motor cortex. Interestingly, these regions were again recruited during action decision (see **Tables 3** and **4** for exact location in MNI-space, *T*-values, and cluster extent). Thus, novices recruited more visual and frontal regions and experts more motor and temporal regions during successful action anticipation.

Based on the local maxima revealed from the early, difficult, occluded video clips individual data were plotted (**Figure 2**) in

Table 1 | Brain regions and local maxima of clusters, recruited by novices during action observation of successful trials compared to unsuccessful trials.

Difficulty level	Brain region	k	X	Y	Z	T
Easy	Temporal pole (BA 38)	5	−52	10	−14	2.8
	Middle temporal gyrus (BA 20)	9	44	8	−34	2.8
Medium	Cerebellum	87	−10	−48	4	10.5
	Fusiform gyrus (BA 37)	87	−28	−38	−20	7.5
	Calcarine (BA 17)	6	−14	−58	10	4.7
Hard	Superior occipital gyrus (BA 19)	46	−18	−82	42	11.9
	Superior occipital gyrus (BA 19)	7	26	−86	36	9.0
	Superior occipital gyrus (BA 19)	7	20	−92	30	6.4
	Precentral gyrus (BA 6)	34	−20	−16	64	6.3
	Middle temporal gyrus (BA 21)	16	−60	−48	−4	5.2
	Cuneus (BA 18)	8	22	−68	20	5.0

In the analyses a voxel-wise threshold of 0.005 uncorrected was used in combination with a cluster threshold of minimum five voxels.

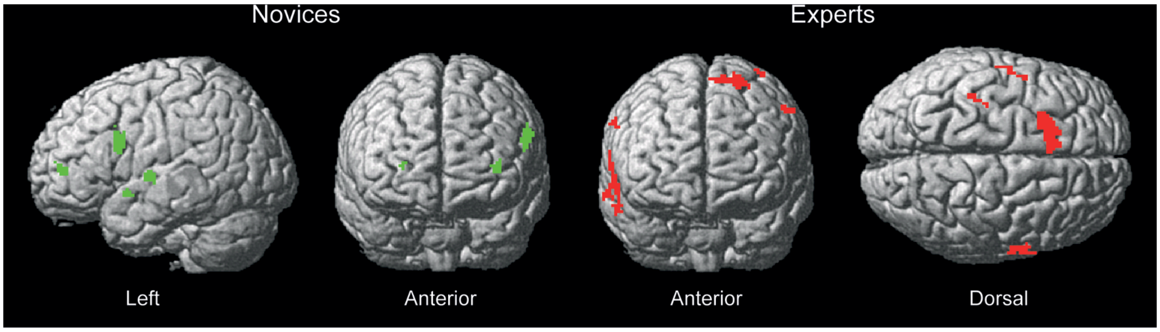

FIGURE 3 | Brain regions recruited for novices and experts during action decision of successful trials compared to unsuccessful trials. Novices rely on pre-frontal regions whereas experts rely on motor/pre-motor regions of the brain. The functional brain response is overlaid on a rendered standardized brain (MNI-space) with a threshold of 0.005 uncorrected only showing clusters with a minimum of five voxels.

Table 2 | Brain regions and local maxima of clusters, recruited by novices during action decision of successful trials compared to unsuccessful trials.

Brain region	*k*	*X*	*Y*	*Z*	*T*
Middle frontal cortex (BA 8)	251	32	18	56	55.2
Inferior temporal sulcus (BA 48)	128	−38	22	16	42.3
Caudate	79	−6	12	6	26.0
Lingual gyrus (BA 19)	14	−22	−68	0	21.5
Inferior temporal sulcus (BA 48)	42	30	30	26	18.0
Insula (BA 47)	48	−30	22	−2	18.0
Superior medial frontal cortex (BA 10)	53	4	34	52	15.5
Inferior frontal gyrus (BA 45)	49	46	32	16	14.4
Caudate	18	8	16	6	14.1
Middle frontal cortex	38	32	28	38	13.6
Rolandic operculum (BA 6)	13	−46	4	16	11.8

In the analyses a voxel-wise threshold of 0.005 uncorrected was used in combination with a cluster threshold of minimum five voxels.

Table 3 | Brain regions and local maxima of clusters, recruited by experts during action observation of successful trials compared to unsuccessful trials.

Difficulty level	Brain region	*k*	*X*	*Y*	*Z*	*T*
Easy	Precentral gyrus (BA 6)	30	36	−26	68	9.8
	Middle frontal gyrus (BA 8)	5	−28	36	44	5.8
	Supplementary motor area (BA 6)	13	10	2	76	4.2
Medium	Cerebellum	30	14	−50	−40	8.5
	Cerebellum	50	38	−56	−38	8.2
	Superior temporal gyrus (BA 42)	50	60	−38	18	7.4
	Precentral gyrus (BA 6)	7	62	4	30	7.0
	Middle temporal gyrus (BA 21)	14	−50	−44	6	5.5
Hard	Middle temporal gyrus (BA 21)	55	−52	4	−32	9.3
	Superior frontal cortex (BA 10)	8	−10	58	8	7.6
	Temporal pole (BA 38)	55	−48	14	−28	6.2
	Middle temporal gyrus (BA 21)	23	−48	−40	4	5.4
	Middle temporal gyrus (BA 21)	10	−44	−6	−14	5.0

In the analyzes a voxel-wise threshold of 0.005 uncorrected was used in combination with a cluster threshold of minimum five voxels.

order to examine individual variability. There were six peaks from the novices and five peaks from the experts plotted (see **Tables 1** and **3**). The individual plots reveal that even though there are some overlap between experts and novices, the overall results show that distinct neural networks are used depending on level of expertise.

DISCUSSION

In the present pilot study we investigated the association between successful action anticipation, expertise, and underlying neural mechanisms. The results are promising and indicate that the present paradigm is suitable to use when studying how motor experience affects our ability to understand relevant information and make a correct anticipation during action observation. However, since the presented data is only from a pilot study great caution should be undertaken when interpreting the results, and before generalizing the results, a large-scale attempt should confirm the findings. The present study followed the logic and stages suggested by Williams and Ericsson (2005) as an approach to study perceptual-cognitive relations in respect to action observation. The first stage was to capture the expert performance. The behavioral data showed that the paradigm was able to separate performance between different groups of individuals with different amount of hockey skill. This is important because it strengthens the validity of the paradigm. Thus, the results further underpin prior evidence regarding how experts outperform novices in action anticipation (Abernethy and Zawi, 2007; Aglioti et al., 2008). We only found a tendency of significant performance differences between experts and amateurs in the behavioral part of this pilot. This is also similar to what others have reported (Wright et al., 2011), which is likely an indication about how difficult it is to create a paradigm that is complex enough to separate the behavior between high skill level and intermediate skill level, but at the same time not too difficult for novices. It

Table 4 | Brain regions and local maxima of clusters, recruited by experts during action decision of successful trials compared to unsuccessful trials.

Brain region	*k*	*X*	*Y*	*Z*	*T*
Middle temporal gyrus (BA 21)	17	−56	−28	−2	11.0
Post central gyrus (BA 4)	8	20	−34	78	10.7
Pre-motor cortex (BA 6)	10	−6	12	72	10.1
Superior temporal gurys (BA 41)	15	50	−34	14	8.0
Inferior temporal gyrus (BA 37)	14	−56	−64	−10	7.0
Superior temporal gyrus (BA 21)	16	64	−28	8	5.8
Middle temporal gyrus (BA 21)	13	−52	6	−30	5.7

In the analyses a voxel-wise threshold of 0.005 uncorrected was used in combination with a cluster threshold of minimum five voxels.

would have been interesting to also have fMRI data on the amateurs since that would give us an indication regarding how much experience that is necessary to recruit similar brain regions as experts. A recent study suggested that intermediate skilled level badminton players recruit brain regions more similar to novice players than expert players during anticipation tasks, although the anticipation performance of the intermediate skilled players was better than the novices (Bishop et al., 2013). The second stage, according to Williams and Ericsson (2005), is to identify the underlying mechanisms. In the present study, we focused on the underlying *neural* mechanisms. The results showed that even the functional brain response during action observation and action decision differ between experts and novices when comparing successful trials with unsuccessful trials. Williams and Ericsson also emphasized on a third stage, to examine how expertise is developed. That stage was not covered in the present study. It has been suggested that most research has focused on capturing expert performance (Williams and Ericsson, 2005), thus the present study has the potential to also deepen our understanding regarding mechanisms associated to experts' superiority during action observation.

The main aim for the fMRI data was to compare correct versus incorrect trials. Thus, this was an attempt to clarify the functional brain regions required for a successful anticipation of actions, and whether such regions differ between novices and experts. Potential differences in underlying neural mechanisms will give us information about if a successful anticipation is handled similar depending on level of motor skill, or if motor experience alters the functional response of the brain. This is a different, and more conservative, approach compared to most previous studies. Interestingly, a similar approach was done recently when Abreu et al. (2012) investigated accuracy in anticipation. They did not, however, make a comparison of successful vs. unsuccessful trials as the present paper, yet, their results confirmed that novices appears to use more pre-frontally oriented brain regions, compared to experts that have increased activity in insular cortex.

Our results indicate that experts, when successfully anticipated action outcome, primarily relied on motor regions in combination with regions of the temporal lobe. Novices instead relied on the visual system during action observation, which is similar to what has been noted during low-level of visual processing (Takahashi et al., 2008). Hence, it appears as if the novices had to search for valuable information in the video clips. Then, during action decision, novices relied on pre-frontal cortex to decide the fate of the action. Pre-frontal cortex is often associated with cognitive demanding tasks such as memory and executive functions (Cabeza and Nyberg, 2000). Thus, it appears as if they needed to use cognitive resources to solve the problem regarding the fate of the action. Experts on the other hand recruited motor regions, which is interpreted as if the experts were able to recruit regions where complex motor representations are stored (Meister et al., 2005), these regions are also well known mirror neuron regions (Rizolatti and Craighero, 2004). By recruiting these regions the experts gathered information from the motor representations, which comprised the result of the action (see Kandel et al., 2000), and thereby could decide the fate of the action. Interestingly, previous results have shown that experts use fewer eye fixations compared with novices when observing actions (Mann et al., 2007), experts are able to extract more meaningful information in shorter time (Williams et al., 1999), and experts have developed specific perceptual-cognitive mechanism to better and more effectively read advanced body cues (Williams et al., 2002). Thus, we suggest that a possible explanation for such behavior may be because experts do not have to rely on a visual search strategy, instead they can directly extract the information from the motor representations and analyze the interaction much faster using parts of the temporal lobe. Activity in the temporal lobe has previously been suggested to reflect analysis of complex human body movements (e.g., dancing) based on kinematic cues in which valuable information is extracted in order to interact with others (Allison et al., 2000). Cross et al. (2006) interpreted activity in the temporal regions as reflecting increased visual scene processing demands. Our study does not offer full support for such conclusion since we contrasted correct and incorrect answers in the analysis. Thus, activation in temporal regions during action observation is not interpreted to reflect visual processing demands since such demand was equal in the two conditions. Cerebellum was also recruited probably reflecting its involvement in movement production and, it has even been proposed that Cerebellum may be interconnected with the mirror neuron system (Sokolov et al., 2010). Taken together, the present pilot study suggests that level of motor skill affects the functional brain response during successful action anticipation.

In the present paper, based on the contrasts performed, we did not find any parietal activation. Parietal activity has been frequently associated with action observation in general (e.g., Buccino et al., 2001), as well as associated with expert athletic performance (see also Yarrow et al., 2009). In a study specifically targeting the role of parietal cortex in prediction of incoming motor actions, Fontana et al. (2012) measured EEG activity in patients with lesions in the parietal lobe while watching a video of a person grasping an object. Results showed how individuals with intact parietal lobe (healthy controls) experienced a readiness potential within the parietal lobe preceding the observation of the upcoming action. No such potential was present in the parietal patient group. Moreover, parietal activation has also been shown by experts more so than novices in studies of motor planning, possibly reflecting their ability for global rather than selective attention, suggesting that experts are more focused and have a more efficient organization (Milton et al., 2007). Thus, the parietal lobe is most likely involved in the prediction of incoming motor actions, which the present study do not argue against. However, based on this data we do not offer support that the parietal cortex is involved when separating between correctly or incorrectly anticipated actions.

One critical point of novelty in the present study is the use of unsuccessful trials as baseline. By doing so we isolated the functional brain response associated with successful anticipation, which in turn is associated with skill. Thus, the differences in brain regions between the groups of novices and experts are based on their hockey skills and not their ability to make correct anticipations. This highlights that even though there are similarities between experts and novices during action anticipation (see e.g., Abreu et al., 2012), when investigating successful anticipation, experts and novices tend to rely on partly different neuronal networks, with experts relying more on motor representations and medial temporal lobe, and novices more on visual and pre-frontal regions. Interestingly it has been suggested that anticipatory information pick-up is related to highly domain-specific memory structures (Yarrow et al., 2009) implying that motor representation created by physical training (in the present paper hockey training) in combination with medial temporal lobe, which is a structure highly involved in memory, is a plausible explanation to our findings. The novices do not have the memories (motor representations) for the actions, and thus must rely on different strategies to successfully perform the task, which was reflected by the use of altered neural systems.

Obviously, because of the limited sample of participants, one must interpret the results from this pilot with great caution, and the results should be confirmed with more participants before generalizing. However, it highlights some interesting findings for future studies of this topic. We must, however, perform this study in large scale with more participants to fully appreciate the proposed relationships. Further, in the present study, even though we used a complex task, it was only with one player. Adding players to create a more complex scenario would be interesting and probably more demanding on the system. However, it is likely that key brain regions for such task will be revealed within similar regions as in the present study. In conclusion, data from the present study support that depending on the level of motor skill of the observer (i.e., task specific physical experience), when correctly anticipating actions different neural systems will be recruited.

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Does motor imagery share neural networks with executed movement: a multivariate fMRI analysis

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Introduction: Motor imagery (MI) is the mental rehearsal of a motor first person action-representation. There is interest in using MI to access the motor network after stroke. Conventional fMRI modeling has shown that MI and executed movement (EM) activate similar cortical areas but it remains unknown whether they share cortical networks. Proving this is central to using MI to access the motor network and as a form of motor training. Here we use multivariate analysis (tensor independent component analysis-TICA) to map the array of neural networks involved during MI and EM.

Methods: Fifteen right-handed healthy volunteers (mean-age 28.4 years) were recruited and screened for their ability to carry out MI (Chaotic MI Assessment). fMRI consisted of an auditory-paced (1 Hz) right hand finger-thumb opposition sequence (2,3,4,5; 2. . .) with two separate runs acquired (MI & rest and EM & rest: block design). No distinction was made between MI and EM until the final stage of processing. This allowed TICA to identify independent-components (IC) that are common or distinct to both tasks with no prior assumptions.

Results: TICA defined 52 ICs. Non-significant ICs and those representing artifact were excluded. Components in which the subject scores were significantly different to zero (for either EM or MI) were included. Seven IC remained. There were IC's shared between EM and MI involving the contralateral BA4, PMd, parietal areas and SMA. IC's exclusive to EM involved the contralateral BA4, S1 and ipsilateral cerebellum whereas the IC related exclusively to MI involved ipsilateral BA4 and PMd.

Conclusion: In addition to networks specific to each task indicating a degree of independence, we formally demonstrate here for the first time that MI and EM share cortical networks. This significantly strengthens the rationale for using MI to access the motor networks, but the results also highlight important differences.

Keywords: motor imagery, functional imaging, fMRI, mental imagery, brain mapping

INTRODUCTION

Athletes have used motor imagery (MI) for decades but recently there has been considerable interest in applying it to the patient population (Braun et al., 2006; Sharma et al., 2006). The general premise is that MI can be used as a surrogate for movement when a disease limits performance, for instance using MI training after stroke (Braun et al., 2006; Sharma et al., 2006; Ietswaart et al., 2011) or Parkinson's Disease (Heremans et al., 2012). The central assumption underlying this aproach is that MI and executed movement (EM) share neural substrates. Demonstrating that imagery and EM share neural substrates, rather than activate similar areas, would significantly enhance the rational for using MI training.

There are numerous behavioral studies that suggest MI and EM involve similar cognitive processes. For example the time taken to imagine a movement is similar to the time taken execute it (Decety et al., 1989). MI is confined by the same principles of motor control that govern EM. The reduction in accuracy with increasing speed (i.e., Fitt's Law) is maintained (Decety and Jeannerod, 1995) as is the asymmetry between dominant and non-dominant hand (Maruff et al., 1999). MI produces similar autonomic changes as EM, with significant increase in heart and respiratory rates (Jeannerod and Frak, 1999; Roure et al., 1999; Kazuo Oishi, 2000).

Given the strength of the behavioral studies it is perhaps not surprising that imaging studies regardless of the modality report that MI activates similar cortical regions to EM (Boecker et al., 2002; Lacourse et al., 2005; Hanakawa et al., 2008; Guillot et al., 2009). The cortical areas involved include the contralateral premotor areas, the primary motor cortex with some caveats, see (Sharma et al., 2008) as well as the cerebellum. These studies typically employed a massed univariate approach and have been useful in identifying significant differences between imagery and EM. For instance the contralateral primary motor cortex activation is both greater (Gerardin et al., 2000; Sharma et al., 2008) and topographically different (Sharma et al., 2008) during EM as compared to MI. The mass-univariate approach is less useful in concluding what neural substrates are common to each task.

Generally this is inferred from involvement of similar cortical structures and a "lack of significant" difference when comparing tasks.

In this study we adopt a model-free approach using tensor independent component analysis to examine the cortical networks that are common to both MI and EM. Unlike the conventional mass univariate approach TICA is a powerful data driven approach capable of exploring similarities in cortical networks. A key aspect of this study is that MI and EM are treated as the same "blinded task" during the production of the independent-components (IC). In other words we make no prior assumptions as to the extent of overlap, if any, between the MI and EM. If the cognitive process of imagery and EM involve similar area but are actually distinct then the analysis will produce networks (i.e., IC) that relate to either MI or EM but not both. However, given the extensive behavioral literatures we hypothesize that three categories of networks will be identified; first, those networks that are present during EM only, which will involve the contralateral primary motor cortex; second, networks that are common to both MI and EM, involving premotor and posterior parietal areas; and finally networks that involve MI only, involving the premotor areas (Sharma et al., 2009a). Understanding which networks MI shares with EM will allow a richer understanding of how MI can be applied to the patient population with maximal effect.

METHODS

SUBJECTS

Fifteen healthy volunteers were recruited through local advertisement with a mean age of 28.4 years ($SD = 6.2$; 7 Male). Subjects overlapped with those reported in (Sharma et al., 2008) where we reported the differential involvement of BA4a and BA4p in MI and EM. They had no past medical history of any neurological, psychiatric or musculo-skeletal disorders and were not taking regular medication. All subjects were righted handed as assessed by the Edinburgh scale (Oldfeld, 1971)and gave written consent in accordance to the declaration of Helsinki and the protocol was approved by the Cambridge Regional Ethics Committee.

All subjects were assessed using the Chaotic Motor Imagery Assessment and were excluded if unable to perform IM adequately. The Chaotic Motor Imagery assessment is described briefly below, for a more detailed description see (Sharma et al., 2006, 2008, 2009a). During all tasks requiring explicit MI, subjects were given specific instructions to perform first person kinesthetic MI; not to view the scene from the 3rd person; and not to count or assign numbers or tones to each finger.

CHAOTIC MOTOR IMAGERY ASSESSMENT

Chaotic Motor Imagery is defined as an inability to perform MI accurately or, if having preserved accuracy, the demonstration of temporal uncoupling (Sharma et al., 2006). Briefly the CMIA consists of three components performed in the order they are described here.

First, subjects are shown 96 A4-sized picture cards of hands (4 different views, 12 rotations, left and right) and asked to identify whether the picture is of a left or right hand (Component 1). A score below 75% correct indicates that the subject is unable to perform accurate MI. Second, subjects are asked to perform MI of a finger sequence task (2,3,4,5,2..; Paced using Auditory cues at 1Hz; fMRI simulation Component 2). The duration of the finger tapping exercise varied and the subject had to confirm their position at the end of each block. Third, subjects are required to perform the same finger taping sequence initially using EM and then using MI (Component 3). During both phases of this test the external auditory pacing rate, which starts at 40 beats/min is increased by 10 beats every 5 s. The break point is defined as the time when the subject is unable to perform the task accurately. Subjects are excluded if the break point is greater for MI than for EM. During all tasks requiring MI, subjects were given specific instructions to perform first person MI; not to view the scene from the 3rd person; and not to count or assign numbers or tones to each finger. Subjects were excluded if unable to perform MI adequately.

FUNCTIONAL MRI

Motor (imagery) paradigm

The fMRI used an established block design (Sharma et al., 2008, 2009b) that consists of auditory-paced (1 Hz) right hand finger-thumb opposition sequence (2,3,4,5, 2. . .) with two separate runs acquired (MI & rest and EM & rest). Subjects were instructed to keep their eyes closed throughout the session. We used individually calibrated bilateral fiber-optic gloves (Fifth Dimension Technologies, SA) to monitor finger movements, excluded inappropriate movement and to confirm the performance of MI—after each MI block subjects confirmed the finger they were currently imagining was the correct "stop finger" for the length of sequence (which varied). After scanning subjects were asked to rate the vividness of MI performance on a seven point scale (Alkadhi et al., 2005).

Data acquisition

A 3-Tesla Brucker MRI scanner was used to acquire both T2-weighted and proton density anatomical images and T2*-weighted MRI transverse echo-planar images sensitive to the BOLD signal for fMRI ($64 \times 64 \times 23$; FOV $20 \times 20 \times 115$; 23 slices 4 mm, $TR = 1.5$ s, $TE = 30$ ms, Voxel Size $4 \times 4 \times 4$).

Image analysis

Analysis was carried out using Tensorial Independent Component Analysis (Beckmann and Smith, 2005) as implemented in MELODIC (Multivariate Exploratory Linear Decomposition into IC) Version 3.09, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). The first 12 volumes were discarded to allow for T1 equilibration effects. Given our hypothesis and the identical temporal design of the MI and EM task, no distinction was made between tasks until the final stage of processing. As 14 subjects (one subject was excluded see below) performed 2 tasks, MI and EM, 28 "blinded" tasks were processed-we use the term blinded as no distinction was made between either imagery or EM during the generation of the IC.

The following data pre-processing steps were applied to the 28 blinded tasks: masking of non-brain voxels; voxel-wise de-meaning of the data; normalization of the voxel-wise variance. No subject moved more than 2 mm. Pre-processed data were whitened and projected into a 52-dimensional subspace using probabilistic Principal Component Analysis where the number of dimensions was estimated using the Laplace approximation to the Bayesian evidence of the model order (Beckmann and Smith, 2004). The whitened observations were decomposed into sets of vectors which describe signal variation across the temporal domain (time-courses), the session/subject domain and across the spatial domain (maps) by optimizing for non-Gaussian spatial source distributions using a fixed-point iteration technique (Hyvarinen, 1999). Estimated Component maps were divided by the standard deviation of the residual noise and thresholded by fitting a mixture model to the histogram of intensity values (Beckmann and Smith, 2004). The time course of each Independent Component was then entered into a general linear model of the convolved block design of Task vs. Rest.

Overall this produces a standard subject score for each IC that incorporates the effect size for each of the 28 blinded task (14 subjects, EM and MI) for the associated spatio-temporal process shown in the spatial map and the time course. An IC was considered to be involved in MI or EM if a one-way t-test found it to be significantly different to zero across subjects. If an IC was significantly involved in both tasks then a paired t-test was performed on the subject score for each task, i.e., MI and EM.

RESULTS

BEHAVIORAL RESULTS

One subject was excluded because of a failure to perform MI satisfactorily. The remaining 14 subjects performed adequately on all aspects of the hand rotation task (Mean = 95.3%; $SD = 4.1\%$), fMRI simulation (Component 2) and Fitts law [mean break point 19% ($SD = 14.2$) less for MI than EM], as well as during the fMRI session. No subject failed to either suppress movement or showed evidence of non-compliance during the fMRI paradigm. Median post-MRI MI scores was 6 (range 4–7).

fMRI DATA

Whole brain analysis

Fifty-two IC were defined by TICA. IC's that identified artifact recognized by previously published patterns and high frequency were excluded by visual inspection (Beckmann and Smith, 2005). Components that were driven by outliers or were not significant ($p < 0.01$) across task were excluded. Components in which the subject scores were significantly different to zero (for either EM or MI) were included. Seven IC remained.

In keeping with our hypothesis there were IC's that are shared between EM and MI (subject scores significantly greater than zero for both tasks) and components that are exclusive to EM (subject score greater than zero for EM only) and to MI (subject score greater than zero for MI only). The whole brain activations and deactivations, time course, variance explained and subject score are shown in **Figures 1–3**. **Table 1** summarizes the areas involved in each component which were labeled using the Juelich Atlas (Eickhoff et al., 2005). We have previously explored the differential involvement of BA4a and BA4p (subdivisions of the primary motor cortex) in MI and EM (Sharma et al., 2008); given the degree of smoothing required for TICA it was not appropriate consider this areas separately in this study.

Independent-components shared by executed movement and motor imagery

Five components (IC1, 2, 3, 8, 9 **Figures 1**, **2**) were significantly involved in both EM and MI (subject scores > 0 for both tasks). These components explained 25.49% of the total explained variance. All of the components significantly correlated with the active blocks of the task. In four of the components (IC1, 2, 3, 9), the subjects score was significantly greater during EM than during MI.

IC1 involved activation of all areas of the right parietal lobe (HIP1-3, SPL, IPC) and to a lesser degree the left parietal lobe (hIP2, SPL) as well as the cerebellum (r7L) and BA44 and premotor areas. IC2 showed activation that was largely limited to the premotor areas bilaterally including PMd and SMA. IC3 showed activation that was predominantly localized to the left hemisphere including motor areas (BA4, cerebellum), premotor (PMd, SMA), somatosensory cortex and left parietal areas hIP2-3 and IPC. The activation patterns of IC8 were largely restricted to subcortical structures notable the thalamus (all areas) and cerebellum with limited involvement of the premotor areas.

IC9 is notable as it is equally involved in MI and EM. This IC involves activation of the preSMA, SMA, BA44 and right IPC (PFm).

IC1, IC2, and IC3 all contained areas of deactivation. This generally involved bilateral dorsal BA4. IC1 contained additional deactivation of the left caudate and SPL in IC3.

Independent-components involved during executed movement only

One component, IC19 was significantly involved during EM only (2.06% of explained variance). Again this correlated with the motor tasks rather than rest. This involved activation of areas typically seen in movement; the contralateral motor cortex, somatosensory cortex and hIP2&3. IC19 involved deactivation of the left medial frontal gyrus.

Independent-components involved during motor imagery only

IC26 was significantly involved during MI only (1.55% of explained variance). This correlated with MI rather than rest. The activation was restricted to the right hemisphere and included the right BA4, premotor and area 3b.

DISCUSSION

Here we use a data led method to report that MI and EM share cortical networks. The majority of the networks involved in the tasks appear to be shared (accounting 25.49% of the total explained variance). One network was exclusive to EM (accounting for 2.06% of the explained variance) and another was exclusive to MI (accounting for 1.55% of the explained variance). That being said a number of the shared networks are significantly more involved in EM than MI. This provides an important foundation for the use of MI as an alternative means to access the motor system in diseases that limit physical performance such as stroke (Sharma et al., 2006).

We report that EM and MI indeed share the vast majority of networks. A key area that appears to be shared is the contralateral primary motor cortex. In previous studies using mass univariate methods there has been varying reports of its involvement (Gerardin et al., 2000; Hanakawa et al., 2003, 2008; Sharma et al., 2008) for a meta-analysis see (Hetu et al., 2013). On a subset of these subjects we have previously reported that MI activates the posterior division rather than the anterior division of the motor cortex (Sharma et al., 2008). In addition

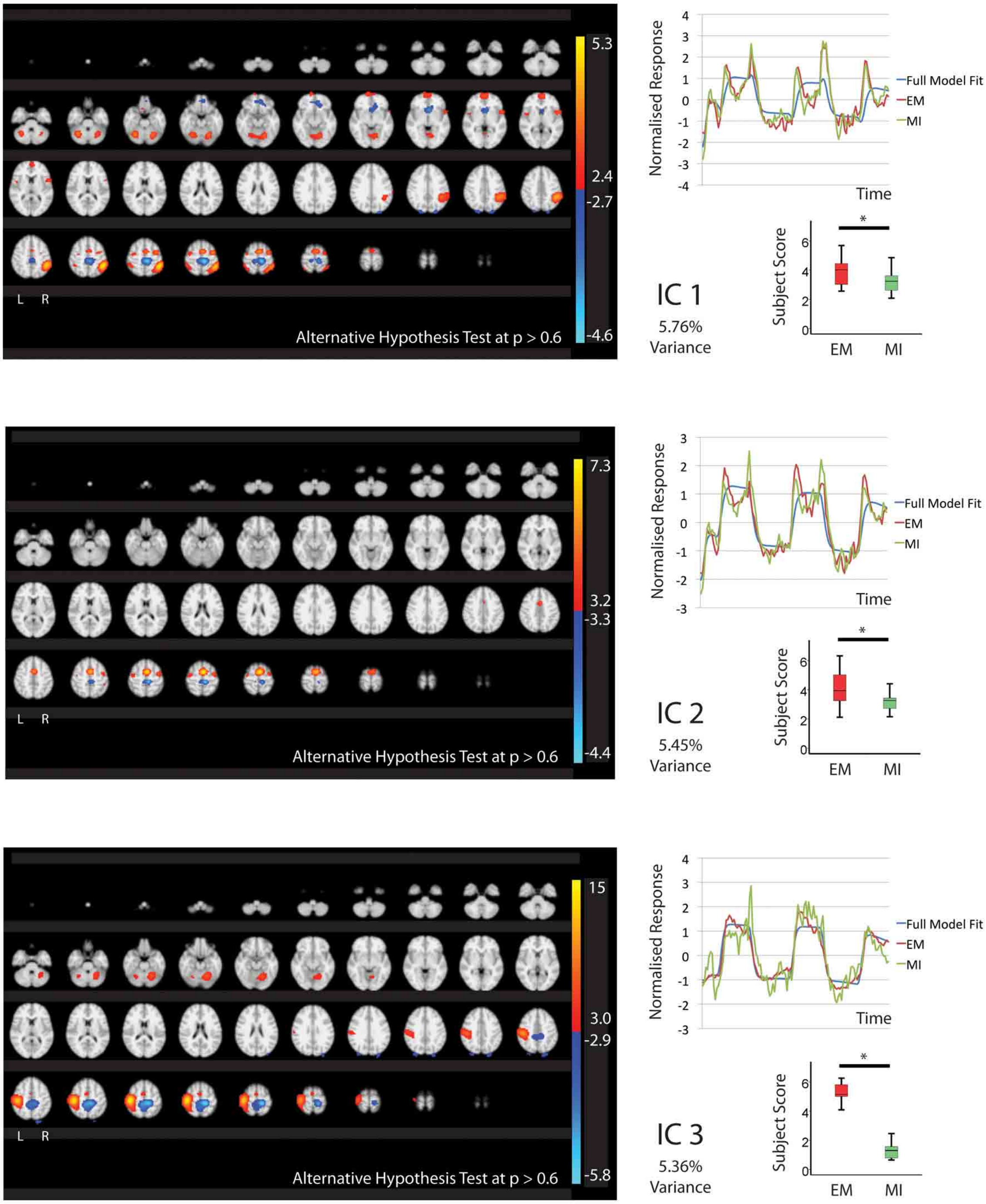

FIGURE 1 | The figures show the involvement of each IC across the whole brain with a standard threshold of $p > 0.6$ (alternative Hypothesis test) and the variance is accounts for out of the total explained variance. The scales show the transformed *z*-score, orange is activation, blue is deactivation. The normalized time course response is shown for each task and the full model fit (Full model fit = blue, executed movement = red, motor imagery = green). The mean subject scores with standard error bars are shown for each task and differences highlighted (executed movement = red, motor imagery = green). The IC's (1, 2, 3) that are shared between executed movement and motor imagery. The time course and subject score for each task are shown. *IC1; $p < 0.01$, IC2; $p < 0.05$, IC3; $p < 0.001$.

to methodological issues with monitoring MI compliance (see Sharma et al., 2006) we have previously suggested that this may explain the lack of BA4 activation often seen in studies of imagery (Hetu et al., 2013).

The motor cortex is a central node in motor learning (Muellbacher et al., 2002) and recovery after stroke (Calautti et al., 2001; Ward and Cohen, 2004; Cramer, 2008; Sharma and Cohen, 2010). Demonstrating that MI includes the contralateral primary

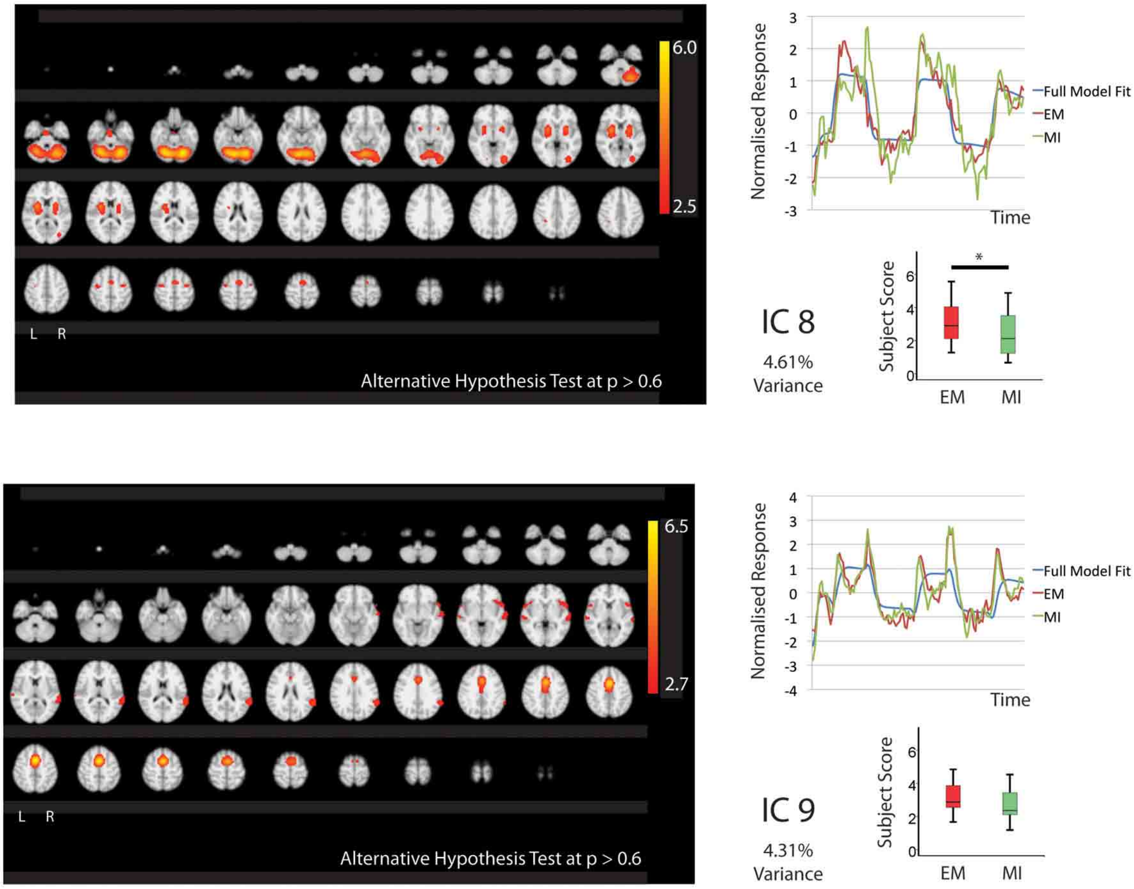

FIGURE 2 | The figures show the involvement of each IC across the whole brain with a standard threshold of $p > 0.6$ (alternative Hypothesis test) and the variance is accounts for out of the total explained variance. The scales show the transformed *z*-score, orange is activation, blue is deactivation. The normalized time course response is shown for each task and the full model fit (Full model fit = blue, executed movement = red, motor imagery = green). The IC's (8, 9) that are shared between executed movement and motor imagery. The time course and subject score for each task are shown. *IC8; $p < 0.05$.

motor cortex strengthens the rationale for using it as a form of training after stroke. The motor cortex has been shown to have a number of different functions (Sanes and Donoghue, 2000). In this context it is likely to be involved in aspects of motor control that precede actual movement (as a result of discharge via the CST). The deactivation of the dorsal aspect of BA4 in IC's 1,2, and 3, needs to be explored further. Consistent with studies using conventional fMRI analysis (Gerardin et al., 2000; Sharma et al., 2008) it should be noted that while IC's involving the contralateral motor cortex are shared between imagery and EM they are more involved in the latter. This raises an important point. Typically MI is used as an alternative means to access the motor system when EM is difficult or not possible (Sharma et al., 2006). Given that we report that the shared networks are activated less during imagery than EM, our results imply that for MI to be as effective as EM the duration of training may need to be greater. Indeed behavioral studies suggest MI training is generally less effective than physical training (Gentili et al., 2010).

The one cortical network that appears to be equally shared between the two tasks involves the supplementary motor cortex (SMA). The SMA been implicated in motor planning and learning (Halsband and Lange, 2006). A previous study has suggested that the role of SMA in MI is to suppress motor output via the motor cortex (Kasess et al., 2008). Although our results to not directly address this point, the observation that the network is equally shared with EM would argue against this view. Effective connectivity of fMRI data has shown that imagery and EM have similar connections (Gao et al., 2011). Indeed studies of the effective connectivity between cortical areas suggests that imagery is capable of highlighting changes not apparent during EM after stroke (Sharma et al., 2009a). There have been numerous studies that use MI to control brain-computer interfaces that typically involve recording from the motor cortex (Wolpaw et al., 2002; Buch et al., 2008, 2012). Although speculative, our results suggest that in principle SMA may be a suitable alternative or additional site for brain computer interfaces (BCI) devices.

It is not surprising that there is a network that is exclusive to EM. Of course the most striking difference between imagery and execution is the discharge via the CST that produces movement and sensory feedback. The cortical areas present in the EM exclusive network involve activation of the contralateral primary motor cortex and the somatosensory cortex. Although the result should

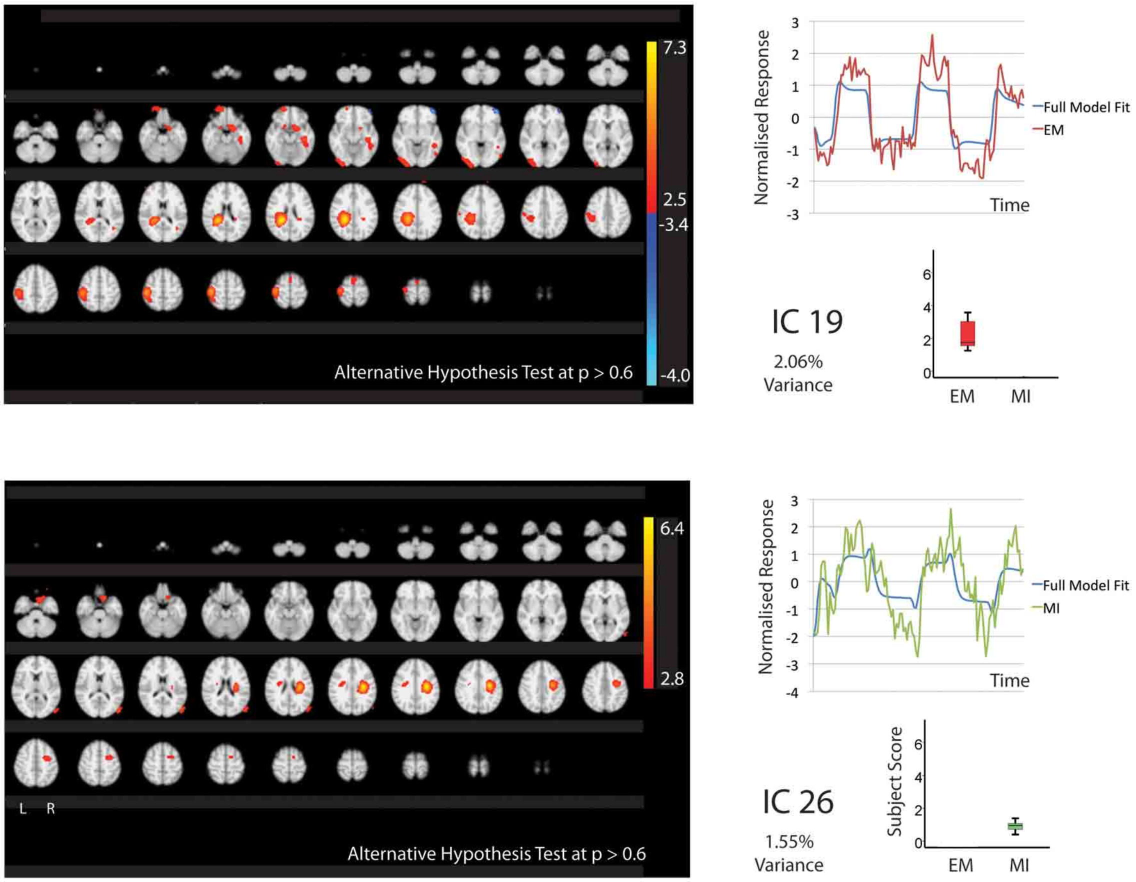

FIGURE 3 | The figures show the involvement of each IC across the whole brain with a standard threshold of $p > 0.6$ (alternative Hypothesis test) and the variance is accounts for out of the total explained variance. The scales show the transformed *z*-score, orange is activation, blue is deactivation. The normalized time course response is shown for each task and the full model fit (Full model fit = blue, executed movement = red, motor imagery = green). IC 19 that is related to executed movement only and IC26 that is related to motor imagery only. The time course and subject score for each task are shown.

not be over interpreted it should be noted that this network is largely restricted to the left hemisphere. Whether this finding would be replicated in similar analysis involving stroke patients would be of interest. It is conceivable that TICA could resolve the debate of whether the bilateral activation often seen after stroke (Calautti et al., 2001; Ward et al., 2003) is related to discharge via the CST or processes that preceed movement. This could be addressed in future studies using similar multivariate analysis.

We report a network that appears exclusive for MI. Typically MI is thought to be a simple surrogate for EM and is often not considered as useful in its own right. Our data further establishes that this is not so. The cortical network involves the ipsilateral motor cortex and BA3a (exclusive to this network) and the ipsilateral PMd (common across networks see **Table 1**). It has previously been shown that PMd is important to motor recovery after stroke (Calautti et al., 2001), particularly in subjects who are more severely impaired (Johansen-Berg et al., 2002). The role of PMd in these cases may be related to action selection and goal directed movement. Whether MI will have greater beneficial effect in that patient population, i.e., more severely affected remains unknown.

Here we have reported that imagery and EM share a number of key networks. While we have commented upon these networks individually further work is required to understand the interaction between them. It is reasonable to presume that the IC related exclusively to EM occurs during discharge via the CST, but to fully understand the relationship between these networks and the underlying cognitive processes will require methods with much greater temporal resolution for example magnetoencephalography (MEG).

TICA appears to be a useful tool in testing hypothesis that explore shared networks. It has its limitations, however. For instance a central assumption in this work is that the two motor tasks have the same temporal profile. It is entirely possible that cortical networks that have different temporal profiles have been overlooked by this method. However, if that were the case then one would expect those areas to have been highlighted by earlier mass-univariate fMRI studies. Furthermore, a recent report has highlighted TICA may not be as robust as Parallel Factor Analysis (PARAFAC) if there is a possible violation of the assumption of spatial independence (Helwig and Hong, 2013). It should be noted, however, that this report only used a simulated data set. The original description of TICA found it to be more robust on simulated and real data sets than PARAFAC (Beckmann and Smith, 2005).

Table 1 | Regions activated in each independent component.

	IC's common to both tasks										IC related to EM only		IC related to MI only	
	IC1		IC2		IC3		IC8		IC9		IC19		IC26	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
BA44	✓	✓							✓	✓				
BA4					✓						✓			✓**
Pre-SMA							✓	✓			✓	✓		
SMA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
PMd	✓	✓	✓	✓	✓		✓	✓			✓			✓
Area 1	✓				✓						✓			
Area 2	✓	✓		✓							✓			
BA3a					✓									✓**
BA3b		✓									✓*			
hIP1		✓												
hIP2	✓	✓			✓						✓			
hIP3		✓			✓						✓			
SPL(7A)	✓	✓												
SPL(7PC)	✓	✓												
IPC(PFt)					✓						✓			
IPC(PFm)		✓								✓				
IPC(Pga)		✓												
IPC(PF)		✓												
Thal_premotor														
Thal_motor							✓	✓						
Thal_Somatosenosry							✓	✓						
TE							✓	✓		✓				
CB	✓	✓			✓	✓	✓	✓						

*Exclusively found in IC19; **Exclusively found in IC26 (Eickhoff et al., 2005).

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A timely review of a key aspect of motor imagery: a commentary on Guillot et al. (2012)

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The timing of motor imagery has recently received attention from a number of researchers, culminating in a comprehensive review by Guillot and colleagues. This paper aims to further explore this issue, building upon the said review to suggest a number of other important timing-related issues. Specifically, we consider the possible role of bio-informational theory (Lang, 1979, 1985) and the recent proposal of "behavioral matching" in conjunction with the PETTLEP model (Holmes and Collins, 2001) of motor imagery. Furthermore, we explore the possibility that timing has important implications for motivational aspects of imagery. We then discuss the potential role of rhythm, an important but often overlooked aspect of skilled motor performance, and its links to the timing issue. Finally, we conclude by offering suggestions for future imagery timing research to examine this relatively under-researched area of imagery.

Keywords: mental practice, mental chronometry, imagery timing, bio-informational theory, rhythm

INTRODUCTION

Imagery is one of the most popular psychological techniques used in sports skill learning. However, despite growing knowledge of how skills are best learned, there is still some lack of agreement regarding the most effective ways to implement imagery interventions. One issue that has received a great deal of recent research scrutiny is the speed at which the imagery should be conducted to have the greatest performance benefits. Imagery can be performed in real time, or there can be a divergence between the time taken to perform a movement and to mentally simulate it. This may be deliberate or because an individual is not capable of producing a vivid image in real time. For example, individuals may perform slow motion imagery deliberately when developing a skill, to enable them to focus more on key aspects of that skill than would be possible when performing real-time imagery (O and Hall, 2009). Also, stroke rehabilitation patients may perform slow imagery as following a stroke motor cognition slows down (González et al., 2005). Alternatively, an athlete may, when mentally simulating a skill, imagine him or herself to perform the skill more quickly than he or she currently does, as faster performance is desirable (e.g., in running a race). A recent review by Guillot et al. (2012) addressed many of the associated issues and provided a clear and comprehensive examination of work in this area. In order to respond to this, we would like to add our own suggestions for future research and raise issues that we believe could further develop understanding of this component of imagery research.

BIO-INFORMATIONAL THEORY

Researchers in sport psychology have long been intrigued by the possible applications of Lang's (1979, 1985) bio-informational theory to motor imagery (see, for example, Hale, 1982, 1994). This theory was proposed to explain the effects of imagery interventions in treating emotional disorders, but the theory also seems to apply well to the imagery of motor skills. Indeed, its tenets have been well-supported in the sport psychology literature (Bakker et al., 1996; Smith et al., 2001; Slade et al., 2002; Smith and Collins, 2004; Wilson et al., 2010). Lang posited that all knowledge is represented in memory as units of information regarding objects, relationships and events. These units of information are termed propositions, of which there are three fundamental categories represented in memory: stimulus, response and meaning propositions. Stimulus propositions are the descriptive referents relating to the external environment. Response propositions describe the responses of the individual to the stimuli in the scene, such as motor activity and autonomic changes. Meaning propositions are analytical and interpretative, adding components of information not available from the stimuli in the situation. They define the significance of events and the consequences of action.

According to Lang (1985), the processing of response propositions accesses the memory representation for the imaged movement, and thus leads to physiological responses in relevant muscles and organs. Also, meaning propositions must be processed to fully access the memory of the action. It is the accessing, and subsequent strengthening, of the memory representation that is hypothesized to enhance performance. We might expect that imagery performed at the same speed as the task is actually performed would be more meaningful to the performer than slower or faster imagery, having stronger meaning propositional content. According to bio-informational theory such greater meaningfulness should translate into more effective imagery, but such a suggestion has yet to be tested from a Langian perspective. In addition, the timing issue has important implications for response propositions and the kinesthesis that results from the processing of these. Specifically, the kinesthetic sensations accompanying a movement are partially dictated by the timing of that movement, as changes in the timing will lead to changes in the pattern of muscle activation that produces the kinesthetic sensations being experienced. This is because movement kinematics change as movement speed changes (for example, Brindle et al., 2006), therefore we hypothesize that real time imagery will be more likely to be associated with realistic, meaningful kinesthesis than will slow motion or fast imagery. However, this has yet to be tested empirically, and thus examinations of the effects of imagery timing on the propositional content of the imagery experience (specifically response and meaning propositions) would be very welcome additions to the imagery literature.

BEHAVIORAL MATCHING

The development of the PETTLEP model (Physical, Environment, Task, Timing, Learning, Emotion, Perspective; Holmes and Collins, 2001) provided some practical guidelines for imagery interventions. The model was based on findings from neuroscience (Jeannerod, 1997) and cognitive psychology (see Lang's work cited in the preceding section). It centered on the premise that a "functional equivalence" exists between imagery and execution of a task. However, a review by Wakefield et al. (2013) further explored this issue and concluded that behavioral matching may be a more appropriate term for the interventions used in most published research on this topic, as the similarity described in these studies is more at a behavioral level, and merely reflects and implies neural equivalence. As such, they recommended that the behavioral aspects of PETTLEP imagery be matched as closely as possible to actual execution of a task.

Timing is one such component of the PETTLEP model and, as such, if behavioral matching is to occur then imagery interventions should be conducted in real time, appropriate to the learning stage of the performer. O and Hall (2009) tested the intentional use of imagery at different speeds, reporting that slow motion imagery was used more frequently when learning a new skill. Timing has also been shown to be adversely affected when imagery is performed in a relaxed condition (Louis et al., 2011). This further supports the notion that imagery should be matched to the behavioral characteristics of physical performance. However, skilled performers can intrinsically control the speed of their imagery (Munroe et al., 2000; Morris et al., 2005). This is interesting in the context of PETTLEP as Holmes and Collins (2001) suggested there may be differences in the imagery experience, and the meaningfulness of it, dependent upon the stage of learning. Despite the mixed findings regarding the relative efficacy of different imagery timings, further research on this topic is important to establish the optimal imagery conditions for enhanced performance.

Recent work in our own laboratories has focused on manipulation of imagery speed within the framework of the PETTLEP model. The work has assessed the impact on performance of sport and fitness-based tasks, with imagery conducted at real time, increased speed and slow motion using video-controlled timing (i.e., using action observation concurrently to imagery, with participants instructed to mentally simulate the movement whilst watching a first-person perspective video of it). Preliminary results have generally revealed a positive impact on performance regardless of imagery speed. However, the real time and slow motion groups have shown the largest performance increases. Therefore, this evidence does not unequivocally support the idea that real time imagery should generally be used to facilitate the behavioral matching process. Indeed, depending on the stage of learning of the performer or their particular performance goals, slow motion may be equally effective, as slow motion imagery has been shown to have advantages for athletes trying to correct a bad habit (Syer and Connolly, 1984). Specifically, slow motion imagery will enable the athlete to see and feel faults in technique in a way that might be impossible with real time imagery, particularly with skills that are performed in a very short space of time, such as specific parts of a gymnastics move or a dive. In such cases the movement would be over so quickly that it would be difficult for the athlete to focus in any detail on specific parts of it whilst imaging in real time. Slow motion imagery, on the other hand, may enable the athlete to explore different parts of the movement more effectively. Thus, the efficacy of real-time versus slow motion imagery may be achieved through slightly different mechanisms, with real-time imagery providing a very meaning-laden and behaviorally-matched imagery experience to enable realistic mental practice (cf. the PETTLEP model, Wakefield et al., 2013) and slow motion imagery enabling an explicit analysis of technique, enabling performance enhancement through modifications made in response to such analysis.

MOTIVATIONAL ASPECTS

Guillot et al. (2012) focused their attention on the cognitive specific function of motor imagery (i.e., the use of imagery to mentally simulate movements), stating that there is no reason to presume that imagery speed might influence motivational imagery's effectiveness. However, cognitive specific imagery may also produce motivational effects, and imagery speed may well be a confounding factor in such effects, particularly in activities where speed is a crucial element of performance. It seems reasonable to presume that imaging such activities faster than they can be carried out at present (such as a sprinter imagining performing a personal best time) may well have strong motivational impact. Conversely, imaging such activities more slowly than would normally be performed (such as a triple jumper imaging performing their run-up in slow motion to help correct a technical fault) would be less likely to have a motivational impact, though the imagery may still serve a very useful purpose. More research is therefore needed to examine the effects of different imagery speeds on the motivational impact of cognitive-specific imagery.

RHYTHMICITY

A further issue relating to the timing of imagery that could benefit from more research is the rhythmicity of the action. Many, if not all, sports skills can be considered rhythmic in nature (Gallahue and Donnelly, 2003), and rhythm, or "temporal invariance of movement components" (MacPherson and Collins, 2009, p.S49), is a crucial aspect of many sport skills. Thus, whereas timing in imagery corresponds to the duration or speed of a global task, rhythmicity relates to the relative timing of different parts of a task, such as when a series of co-ordinated actions are performed.

Links have been shown between rhythmicity and performance of a number of sports including gymnastics (Pica, 1998), golf (Kim et al., 2011a), dance (Laurence, 2000), fencing (Borysiuk and Waskiewicz, 2008), swimming (Zachopoulou et al., 2000) and tennis (Sogut et al., 2012). Rhythm, like imagery, is an important component in ensuring effective preparation for competition (MacPherson and Collins, 2009). Research has shown that as skill level improves, there is a decrease in the degree to which the movement sequence varies (Rose and Christina, 2006). Thus, it could be argued that increased rhythm is achieved when learning progresses and stable rhythmic structures are apparent in mature motor skill patterns. However, research has shown increased temporal variability, thus reduced rhythm, with increasing age (Kim et al., 2011b). The rhythm of the action to be imaged may, therefore, have an impact on the optimal imagery conditions, and should be considered when designing interventions. Also, the degree to which rhythm is a necessary component of a particular skill may influence the effect of varied timing of interventions on that same skill. MacPherson and Collins (2009) argue that promoting mechanisms controlling the consistency of timing and rhythm is a worthy endeavor in the field of sport psychology.

Furthermore, Calmels et al. (2006) revealed that, whilst total time was comparable between imagery and execution, differences were apparent in the relative timing of the components. Therefore, focused imagery and observation interventions may not assist in ensuring and maintaining the rhythmical aspects of the components of sports skills: an area that warrants further research. The influence of factors such as imagery modality, agency and perspective on relative timing of movement components during imagery may be particularly worthwhile, to determine whether behavioral matching of imagery and movement execution may be more effectively achieved when such variables are manipulated in particular ways. For example, research (White and Hardy, 1995; Hardy and Callow, 1999) has found that third-person visual perspective imagery is more effective at enhancing the performance of form-based skills, such as gymnastic tasks, than the first person visual perspective. Given that rhythm is often a crucial component of such skills, and that the third person perspective provides a model of performance from which key aspects of the movement can be extracted, including rhythm, we hypothesize that external visual imagery may be more effective in reinforcing the desired rhythm than internal visual imagery. This is especially likely if the external perspective imagery is accompanied by kinesthesis, as imaging the feel of the movement may also help the imager mentally simulate the desired rhythm, which will no doubt be associated with particular kinesthetic sensations. The testing of such hypotheses would be a very useful addition to the imagery literature.

CONCLUSION

In conclusion, we have highlighted some further areas that may impact imagery timing and the efficacy of different intervention speeds. Each of these areas would benefit from further research. Indeed, simply from a practical point of view, completing imagery at an increased speed enables more "sets" to be completed within a given intervention period. Additionally, this would also benefit performers in situations where there is a lack of available time (i.e., between points in a match). However, an increased speed of imagery could well have a detrimental effect on the quality of the imagery, though this is an issue that remains to be investigated. It is therefore important to fully understand the benefits and drawbacks of the varying timings of imagery, in order that the correct intervention can be matched to the age, performance level and sport of the individual. As such, we recommend future research should focus on the potential motivational effects of imagery timing, the link to meaning and the potential overlap with producing rhythmical action.

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The impact of sensorimotor experience on affective evaluation of dance

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Past research demonstrates that we are more likely to positively evaluate a stimulus if we have had previous experience with that stimulus. This has been shown for judgment of faces, architecture, artworks and body movements. In contrast, other evidence suggests that this relationship can also work in the inverse direction, at least in the domain of watching dance. Specifically, it has been shown that in certain contexts, people derive greater pleasure from watching unfamiliar movements they would not be able to physically reproduce compared to simpler, familiar actions they could physically reproduce. It remains unknown, however, how different kinds of experience with complex actions, such as dance, might change observers' affective judgments of these movements. Our aim was to clarify the relationship between experience and affective evaluation of whole body movements. In a between-subjects design, participants received either physical dance training with a video game system, visual and auditory experience or auditory experience only. Participants' aesthetic preferences for dance stimuli were measured before and after the training sessions. Results show that participants from the physical training group not only improved their physical performance of the dance sequences, but also reported higher enjoyment and interest in the stimuli after training. This suggests that physically learning particular movements leads to greater enjoyment while observing them. These effects are not simply due to increased familiarity with audio or visual elements of the stimuli, as the other two training groups showed no increase in aesthetic ratings post-training. We suggest these results support an embodied simulation account of aesthetics, and discuss how the present findings contribute to a better understanding of the shaping of preferences by sensorimotor experience.

Keywords: aesthetics, neuroaesthetics, training, motor learning, observational learning, dance

INTRODUCTION

Human interest in aesthetics has been present for millennia, with some of the earliest evidence coming from the Palaeolithic cave paintings in Lascaux and the so-called Venus figurines (De Smedt and De Cruz, 2013). Until recently, the study of aesthetics resided within the humanities, as philosophers, ethnographers and artists grappled with questions concerning what it meant for an object, song, poem, or dance to be considered beautiful or aesthetically pleasing. Only recently has academic interest in aesthetics broadened to also include scientific studies. In particular, neuroscientists and experimental psychologists have begun to study the cognitive and brain processes underlying a perceiver's aesthetic experience when beholding an artwork (Zeki and Lamb, 1994; Ramachandran and Hirstein, 1999; Vartanian and Goel, 2004).

A considerable number of researchers have been interested in exploring the behavioural consequences or neural substrates of aesthetic evaluation of static, visual artworks, such as paintings and sculpture (Berlyne, 1974; Cela-Conde et al., 2004; Kawabata and Zeki, 2004; Leder et al., 2004; Jacobsen et al., 2006). Far less attention has been devoted to exploring the brain and behavioral manifestations of the aesthetics of performing arts, such as theater and dance. We argue that dance is a particularly rich art form to investigate due to an equally strong reliance upon a dancer's creative and artistic sensibilities as well as his or her physical abilities. Moreover, dance is the only form of art based solely on movement of the human body. As such, behavioral and neuroscientific methods are starting to offer new insights into subjective and objective features of the relationship between movement and cognition, including action perception coupling and the perceiver's aesthetic experience of watching dance (Bläsing et al., 2012; Cross and Ticini, 2012).

Several neurocognitive investigations have incorporated dance into experimental paradigms to advance knowledge of how we perceive others' bodies in action, as well as how an observer's action experience influences perception of others' actions. Through use of neuroimaging (Calvo-Merino et al., 2005, 2006; Orgs et al., 2008), behavioral (Calvo-Merino et al., 2010; Stevens et al., 2010; Jola et al., 2012b), and combined neuroimaging and behavioral approaches (Brown et al., 2006; Cross et al., 2006, 2009a,b), these studies demonstrate how being in possession of a highly skilled movement repertoire influences perception of other people in motion (for a comprehensive overview, see Bläsing et al., 2012). One relevant strand of scientific inquiry that has used dance as a medium for understanding links between perception and action focuses on the aesthetic value of a movement to an observer (Cross and Ticini, 2012). Calvo-Merino et al. (2008) did this by investigating brain processes that underlie dance-naïve participants' aesthetic experience when watching dance. They identified what kinds of movements were most appealing to spectators and brain areas that showed greater activation when spectators watched movements that were enjoyable to observe compared to those that were less enjoyable. The authors found that visual and sensorimotor brain areas play a role in an automatic aesthetic response when viewing dance movements that are rated as enjoyable to watch.

In a subsequent fMRI study, Cross et al. (2011) aimed to draw together earlier research on action experience with questions about aesthetics by quantifying the relationship between observers' ability to physically perform dance movements and the degree to which they liked watching them. In this study, participants rated their perceived physical ability to perform dance movements (after Cross et al., 2006) and also gave an aesthetic rating of each dance movement on the like-dislike dimension of Berlyne's (1974) aesthetic evaluation scale. The behavioral data from this study showed that participants liked movements more that they perceived as difficult to perform. This result suggests that lesser embodiment (or perceived physical ability) of an observed action is associated with greater enjoyment when watching that action. While the relationship between physical familiarity and enjoyment was very clear in the Cross et al. (2011) study, this finding stands in strong contrast with a number of other experimental investigations into the relationship between familiarity and enjoyment of a stimulus. In non-dance domains, a consistent finding is that individuals tend to like objects, paintings, text, and even abstract visual stimuli more when they are familiar with them (Sluckin et al., 1982; Hekkert et al., 2003; Jacobsen et al., 2006; Bohrn et al., 2013). Such discrepant findings from the dance and non-dance domains of experimental aesthetics research underscore the need to clarify the relationship between an observer's aesthetic experience and familiarity in the physical domain. The primary aim of the present study was to clarify this relationship.

While it has been shown that physical experience with complex, full-body dance actions modulates structure and function within the human brain (Calvo-Merino et al., 2005, 2006; Cross et al., 2006, 2009a,b; Hänggi et al., 2010), it remains unclear whether and how these changes might be correlated with changes in aesthetic preference. Put in other words, it is unknown how increasing an observer's physical experience with dance movements might change his or her aesthetic response to watching those same movements. In non-dance domains, several studies have demonstrated that acquired expertise influences aesthetic judgments. Behavioral studies have shown that the level of an observer's expertise modulates his or her aesthetic evaluation of artworks (Zajonc, 1968; Sluckin et al., 1982; Schmidt et al., 1989; Hekkert and van Wiering, 1996), and brain imaging experiments have confirmed that acquired expertise is associated with changes in brain structures underlying perceptual and memory processes (Bangert et al., 2006). Together, these studies suggest that an art-viewer's expertise changes how works are perceived and judged. To date, it remains unknown how physical experience might shape a viewer's aesthetic experience of watching dance.

Based on the evidence reviewed above, it seems likely that learning to perform a particular dance movement could influence an observer's aesthetic experience of watching that movement. Montero (2012) describes this situation in behavioral terms. She maintains that dance training can facilitate a kinesthetic experience when watching dance without which some aesthetic aspects of dance performance, such as grace, power, and precision, may go unnoticed. Thus, Montero argues, physical expertise facilitates a more differentiated view on dance performances. The present study attempts to directly address the link between physical ability and aesthetic experience using a dance-training paradigm. Our primary aim was to quantify how the relationship between these two variables is manifest behaviorally. By using a popular video game system that teaches players to mirror hip-hop/popular dance sequences performed by avatars, we controlled for specific features of the physical stimuli and participants' training experience, including movement, music, costumes, and background. Thus, our approach moves a step beyond the short isolated dance clips with minimal costume or setting information used in most prior studies that have used dance to study psychological or neuroscientific questions (c.f., Bläsing et al., 2012), and helps to create a more ecologically-valid, natural performance and spectator experience (c.f., Jola et al., 2012a,b).

Participants without prior dance experience were split into three training groups: a group that physically practiced several dance sequences (physical training group), a control group that simply watched and listened to the dance training music videos (which included dancing avatars; audiovisual experience group) and another control group that only listened to the soundtrack that accompanied the dance training music videos (auditory experience only group). The audiovisual experience group was included to examine effects of embodiment *per se* on aesthetic evaluation (as participants in this group spent the identical amount of time as the physical training group watching and listening to the video stimuli) and the auditory experience only group was included to examine the impact of increasing familiarity with music on aesthetic ratings.

Distinct predictions were formulated for how different training experience should impact aesthetic judgements in the present study. Before participants began any form of training, we expected to replicate the behavioral findings of Cross et al. (2011) by demonstrating greater liking of more difficult movements. In terms of how the training manipulation should impact perception, separate predictions were formulated for each training group. For the physical training group, two alternative predictions can be distinguished. First, if increased physical experience has the same effect as increased visual familiarity with paintings (Jacobsen et al., 2006) or conceptual familiarity with texts (Bohrn et al., 2013), then we would expect these participants to like the movements more after 4 days of dance practice. Alternatively, if the relationship between aesthetic enjoyment and physical ability reported by Cross et al. (2011) endured after several days of physical practice, then we would expect participants in the physical training group to like the movements less that they have learned to perform through physical practice. For participants in the audiovisual experience group, even without ever attempting to perform the observed sequences, we expected their ability to dance the sequences they watched throughout training to improve somewhat from this observational learning context (c.f., Mattar and Gribble, 2005; Torriero et al., 2007; Cross et al., 2009a). As a consequence of this, we expected aesthetic ratings to change in the same direction (but perhaps to a lesser degree) as those from participants in the physical training group. Finally, for participants in the auditory experience only group, we did not expect their aesthetic experience of the dance movements to change, as this type of training should not result in any changes in their ability to perform the dance movements associated with the songs listened to during training.

METHODS

PARTICIPANTS

Sixty-two participants (44 females, mean age = 22.60 years; *SD* = 3.38) were recruited from Bangor University to participate in a 1-week dance training study. All participants were matched across the three different training conditions in terms of age and prior dance experience. Whereas we sought to include only participants who had no prior dance experience, it was impossible to assemble a participant sample without any reported experience with dance classes or playing dance video games. Thus, we categorized participants who had less than a half-year of formal dance training as non-dance experienced, as was done in other dance training studies (Cross et al., 2011). No differences between experienced and inexperienced participants were found in relation to the research question[1].

Two participants were excluded from the final study sample, because they did not respond to more than 10% of the trials of the aesthetic rating tasks. Thus, the final sample size was 60 participants, with 21 participants in the physical training group, 19 participants in audiovisual experience group, and 20 participants in auditory experience only group (**Figure 1A**). Bangor University's ethical research committee approved all components of the study. All participants gave informed consent and received monetary compensation (in the form of gift vouchers) or course credits for their participation.

STIMULI AND APPARATUS

Physical performance measures

We chose three sequences from the database of the Xbox 360 Kinect™ game Dance Central 2 (Harmonix Music Systems, Cambridge, MA), according to the variety of dance movements and their difficulty level. The sequences lasted an average of 2:23 min (from 2:19 to 2:30 min). Dance clips were specifically chosen that contained those movements previously shown to be most appealing to dance naïve participants, such as whole body movements with significant displacement of the body in space (like jumping; Calvo-Merino et al., 2008). Furthermore, by using

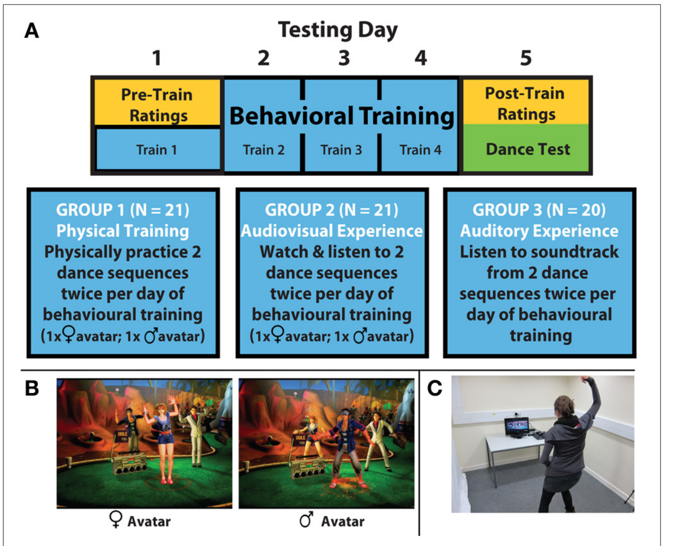

FIGURE 1 | Key elements of experimental procedures, stimuli, and apparatus. (A) Participants partook in 5 consecutive days of testing, with pre-training ratings of the stimuli collected on the first day and post-training ratings collected on the fifth and final day of testing. Participants took part in four identical training sessions (with training experience dependent on group) on days 1–4 of the experiment. Following collection of post-training ratings on day 5, participants were asked to perform the two sequences they had some kind of experience with during training, as well as one novel sequence. **(B)** Illustrations of the female avatar and male avatar used in the Dance Central™ video game. **(C)** Laboratory set up for physical training with the Xbox Kinect™ dance video game.

a classification given by the Xbox Kinect™ system (general difficulty level from 1 to 7), we chose clips with medium difficulty levels (3–5, respectively), to ensure that all participants would be able to perform them, but would still be challenged across the 4 days of training. In addition, within each general difficulty level, it was possible to specify further the level of difficulty for an individual sequence, which represents the complexity and rapidity of changing dance movements (easy, medium, and difficult). We chose a medium difficulty rating for all sequences. Two sequences were used for all three training group, and a third novel sequence was introduced on the final day of testing for all groups to attempt to physically perform a sequence with which they had no prior experience. The objective of this "surprise dance test" was to record a physical ability score for each participant, as well as to determine whether any participants who had not trained with the Kinect™ system might nevertheless have advanced dance abilities. Furthermore, this novel sequence enabled us to examine any potential carry-over effects within the physical training group (see also Cross et al., 2009a,b).

Affective judgment measures

For the aesthetic rating task, the two trained sequences were edited to create 20 short dance clips, 10 from each sequence, performed by both male and female avatars. Participants encountered these 20 short sequences, which ranged in length between 5 and 7 s, before and after training in a task used to assess aesthetic evaluation of the movements. Each clip was selected to contain one main movement, repeated at least twice (such as two

[1]Three MANCOVAS were evaluated with experience (yes/no) as independent variables and post-measures of Question 1–5 as dependent variables. The multivariate tests revealed no significant influences of experience in any of the three groups ($p = 0.443$; $p = 0.357$; $p = 0.101$, respectively). However, these values should be interpreted with some caution due to the fact that participants' experience was coded only according to binominal variables.

consecutive hip swivels). As a general heuristic, all sequences of medium difficulty in the Dance Central 2 game comprise approximately 10 core movements that are repeated and arranged in different orders according to the individual song.

PROCEDURE

Participants arrived on the first day with no prior experience playing the Dance Central 2 video game. Participants filled in The Brunel Mood Scale (BRUMS) developed by Terry et al. (2003). This questionnaire, which is based on the Profile of Mood States, contains 24 questions divided into six respective subscales: anger, confusion, depression, fatigue, tension, and vigor. The items are answered on a 5-point Likert scale (with anchors 0 = not at all; 4 = extremely). We collected these data to ensure that any effects that might emerge across the days of training were not simply due to differences in mood unrelated to the task. We did not observe any difference of mood across groups over the week [$F_{(6.304,\ 185.980)} = 0.450$, $p = 0.852$]. Participants then rated the 20 short movement clips on five different questions based on an eight-point Likert scale (anchors: 1 = not at all; 8 = extremely). Movement clips (including the corresponding audio track) were presented to the participants with MATLAB R2010a Psychtoolbox3 in a random order. The five questions, based on those asked in the Cross et al. (2011) study, were presented in a random order after each sequence and designed to assess participants' affective appraisal of the movement just watched, as well as how complex and engaging they found the movement to be. The questions were "How much did you like the dance performance you just watched?," "How complex did you find the dance performance you just watched?," "How interesting did you find the dance performance you just watched?," "How much would you enjoy trying to perform the movement right now?," and "How much did you like this clip of music?"

After performing this rating task, each participant was assigned to one of the three training groups based on the assessment of his or her previous dance experience/abilities. For the physical training group, the two selected dance sequences were presented to the participants using the Xbox Kinect™ system twice in a random order (once with a female and once with a male avatar (**Figure 1B**); for a total of four dance sequences practiced each day). Participants stood in front of a TV screen and watched the avatar performing a dance sequence. Simultaneously, participants mirrored the movements as well as they could (**Figure 1C**). The Kinect™ sensor captured their movements to calculate a total score for movement accuracy, and also rated participants' overall performance on a 5-point star scale for each performed sequence. The number of stars awarded after each dance performance takes into account overall movement fluency as well as the number of well-executed movements in a row. At the end of each training day, participants from the physical training group were asked to give their subjective rating of their ability to perform the dance sequences ("How well did you know the dance sequence") and their feelings while dancing ("How did you feel during performing the dance sequences") on a 5-point Likert scale.

For the audiovisual experience group, the four original dance sequence videos that the physical training group trained on (two sequences each danced by a male and female avatar; including soundtracks) were presented to participants on a desktop computer with MATLAB R2010a. Participants were asked to watch the avatar perform the dance movements while sitting still. Furthermore, an attention maintenance task was added to each sequence to make sure that the participants paid attention to the stimulus material. Whenever the participants saw a fixation cross in the middle of the screen (during the video sequences), they had to push the right arrow key on the computer keyboard as fast as possible. This fixation-cross appeared randomly with a mean spacing time of 10 s.

For the auditory experience only group, participants listened twice to the soundtracks belonging to the two original video sequences. The computer screen remained black. The condition fulfilled the function of a control condition, because no visual stimuli were presented that should impact participants' dance ability. To make sure that participants paid attention to the music, random beeps was added to the music and whenever the participants heard it, they had to press the right arrow button as fast as possible. Similar to the attention task of audiovisual experience group, the beeps occurred randomly with a mean spacing time of 10 s between beeps.

On the 3 consecutive days of training (days 2–4 of the experiment), all participants came to the lab and repeated the training procedures with the same sequences they rehearsed on day 1. On the fifth and final day of testing, all participants returned for a post-training test. Each participant had to rate the same set of 20 dance clips they had rated on day 1, prior to their first training session. Then, all participants (including those who had been in the audiovisual training condition and the audio only training condition) performed three dance sequences. Each participant had to perform the two sequences they had experienced some aspects of during training, as well as a surprise, novel dance sequence to which participants had not yet been exposed in the course of the experiment. All participants performed each of the three sequences once (randomly ordered across participants). For the two groups of participants who did not train with the XBox Kinect™ system (audiovisual and auditory experience only groups), the experimenter described the task they would be performing, and care was taken so that each participant clearly understood how to reproduce the movements of the avatar and thus play the game correctly. Dance accuracy scores calculated by the Kinect™ system were recorded for the three dance sequences and all participates were asked about their perception of their ability to perform these sequences. They were asked to rate their ability to perform the dance sequences ("How well did you know the dance sequence?") and their feelings ("How did you feel during performing the dance sequences?") on a 5-point Likert scale for both the two trained sequences and the novel sequence.

We did not expect to find differences between groups for performance of the novel sequence, as the sequence was new to all participants (and clearly distinct from the trained sequences practiced by the physical training group). As the novel sequence was added to the post-training follow-up test after the start of the study, it was not possible to completely counterbalance all sequences beforehand. Thus, the novel sequence in the post-training follow-up test as the same for all participants [2]. At the end of the fifth testing session, participants completed a questionnaire on their attitudes and preferences about dance as well as a questionnaire about their openness to experience. As these data were collected to address another experimental question, they are not considered further in this paper.

DATA ANALYSIS

Physical performance

For the physical training group, participants' scores were recorded with the Kinect™ system. However, due to the complexity and somewhat opaque nature of the Kinect™ scoring system, it was necessary to devise a method for generating a numeric score that took into account all elements of performance, including raw dancing score, bonus points for number of nice moves (denoted by green stones in the final score summary), flawless moves (denoted by diamonds in the final score summary), and number of stars awarded to each performance (stars correspond to a combination of several nice or flawless moves performed consecutively) [3]. We calculated an overall score for each performed sequence based on the following algorithm: overall score = number of green stones*5000 + number of diamonds*10000 + stars*1000 + raw numeric score. By taking into account all the "bonus points" scored by participants, this ensured that all aspects of the performance were considered as part of the final score. Using this algorithm, we created an objective measurement of each participant in the physical training group's physical ability to perform each dance sequence at the individual training sessions. We then ran a repeated-measure ANOVA to investigate whether this group's dance scores increased across their daily training sessions.

We analyzed the subjective physical ability ratings reported each day by the participants of the physical training group, after they completed their physical practice. They were asked to rate their ability to perform the dance sequences ("How well did you know the dance sequence") and their feelings while dancing ("How did you feel during performing the dance sequences") on a 5-point Likert scale. The final analysis of performance ability was run on dance scores from all three groups from the post-training surprise dance test.

[2] As the surprise dance test measure was added to the experiment after testing had already commenced, the first five participants did not perform the novel sequence in the follow-up surprise dance retest. Thus, all data reported on this measure come from a subset of 57 participants from the total sample of 60 participants.

[3] To our knowledge, definitive guide for precisely how the Xbox Kinect™ system scores movement is not available. Our attempts to contact Microsoft to get this information were unsuccessful, but ample searching of video game web forums revealed information about the relative quality of green stones and diamonds, as well as what the stars correspond to. Thus, although our scoring algorithm is not directly calculated from the automated Kinect™ numeric score generated at the end of each dance performance, it is based on accurate relative values of the video game feedback, and as all participants were scored by the same system, any bias or inaccuracies in our scoring algorithm apply equally across all participants' dance scores, and thus should not negatively impact results.

Affective judgment

In order to address our main question whether different kinds of experience with whole-body actions might change observers' affective judgments, we evaluated training effects on ratings by calculating a difference score for each participant between post-training and pre-training ratings. Standard inference statistics were used to compare the performance and judgments of the groups in critical conditions and pairwise comparisons (Bonferonni corrected) were subsequently used to look into any differences in more detail. Degrees of freedom reflect the Greenhouse-Geisser correction where sphericity has been violated. Finally, to further explore how the current data relate to behavioral findings reported by Cross et al. (2011), we computed a correlation between participants' ratings of liking and complexity both before and after training.

RESULTS

PHYSICAL PERFORMANCE

To determine whether participants in the physical training group improved their performance on the dance sequences they trained on for 4 consecutive days, we ran a repeated-measures ANOVA with dance score across the 4 days of training as the within-subjects variable. This analysis revealed that participants' dance scores significantly improved over the 4 days, $F_{(3, 18)} = 11.386$; $p < 0.001$, and the test of within-subjects contrasts reveals that this pattern is best captured in a linear contrast, $F_{(1, 20)} = 21.792$; $p < 0.001$ (**Figure 2**). Further investigation into differences between individual days of training revealed that a significant improvement was only observed from the first to the second day of training ($p < 0.001$).

With a repeated-measures ANOVA, we analyzed participants' responses to surveys querying their subjective feelings about their performance after each training session. This analysis demonstrated a clear increase day after day of participants' subjective feelings of knowing the sequences [$F_{(4, 80)} = 47.242$; $p < 0.001$; **Figure 3A**]. It is of note, however, that no change was seen across training days in terms of how good they felt

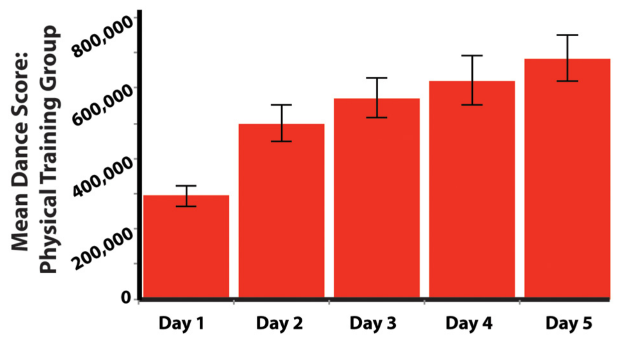

FIGURE 2 | Mean dance scores for the physical training group across the experiment. Participants in the physical training group practiced the same two dance sequences across the 4 days of training, and then performed the same sequences one final time on the post-training dance test on Day 5. See main text for how scores were calculated based on Xbox Kinect™ output.

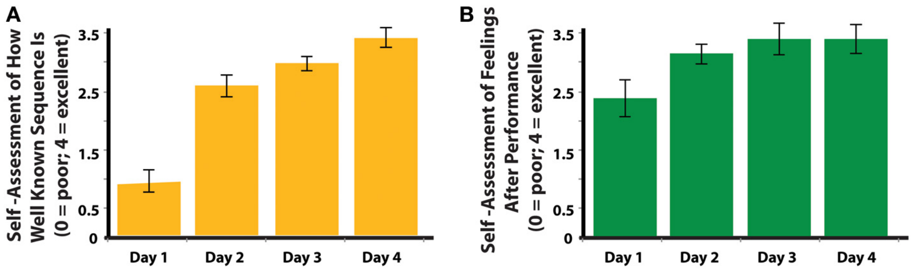

FIGURE 3 | Self-assessment by participants in the physical training group, collected each day after physical practice. (A) Participants' assessment of how well they thought they knew the sequences they just performed. **(B)** Participants' assessment of how they felt after each day of training.

whilst physically performing the sequence [$F_{(1.15,\ 23.04)} = 1.740$; $p = 0.201$; **Figure 3B**]. As participants' dance scores improved (**Figure 2**), so did their subjective feelings of how well they know the sequences (**Figure 3A**).

For the third analysis of physical performance, scores were compared between all participants' performance of the two trained sequences (averaged together), and the one novel sequence, on the fifth day of the study. For the trained sequences, results show that depending on the training group, participants performed differently on the fifth day [$F_{(2,\ 53)} = 28.850$; $p < 0.001$; $\eta^2 = 0.521$]. Participants from the physical training group performed better than those from the audiovisual experience and auditory experience only groups ($p < 0.001$). No differences in performance were found between the audiovisual and auditory experience only groups ($p > 0.900$). For the novel sequence, we found a weaker difference between groups, suggesting that training had less of an effect on participants' ability to perform the new sequence [$F_{(2,\ 53)} = 3.565$; $p = 0.035$; $\eta^2 = 0.119$]. A significant difference emerged between the physical training and the audiovisual experience groups ($p = 0.036$) but not between the physical training group and the auditory experience only group or between the audiovisual experience group and the auditory experience only group ($p = 0.713$, $p = 0.469$, respectively; **Figure 4**).

As a whole, all groups showed better performance for the sequences they had some kind of experience with during the week of training (either physical, audiovisual, or auditory only) compared to the novel sequence (all $p < 0.001$). While we believe the most likely interpretation of this finding is that increased familiarity in any domain (whether motor, visual, auditory, or all three) leads to performance benefits, this finding could also be explained by some kind of inherent difference in sequence difficulty between the two trained sequences and the novel sequence. Future research could explore this possibility.

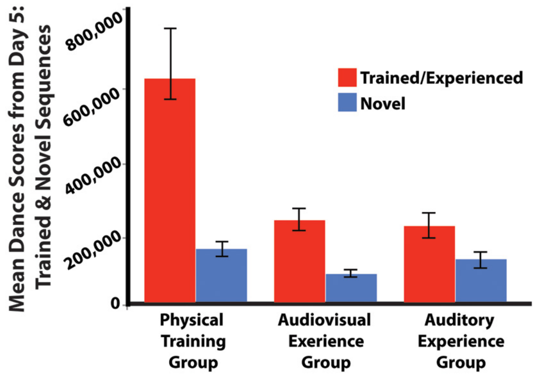

FIGURE 4 | Mean dance scores for each training group for the two dance sequences they have had some kind of prior experience with, as well as one novel dance sequence, collected on the final day of the experiment. Only participants in the physical training group had prior experience with dancing any of the sequences.

AFFECTIVE JUDGMENT

The principal aim of this study was to evaluate how different kinds of experience with complex, full-body movements influence affective judgment of these movements. After computing the difference scores (post-training ratings - pre-training ratings) for each participant on short clips of the dance sequences, we conducted a multivariate ANOVA with participants' ratings as the dependent variable, the five questions as the independent variables (Like watching? How complex? How interesting? Enjoy performing? Like music?) and the three training groups as a between-subjects factor. Results indicate that training condition had a significant effect on the post-training questions of aesthetic evaluation that assessed how much participants liked the dance clip [$F_{(2,\ 57)} = 3.843$; $p = 0.027$; $\eta^2 = 0.119$], how interesting they found the dance movement [$F_{(2,\ 57)} = 3.830$; $p = 0.027$; $\eta^2 = 0.118$], how enjoyable participants rated performing the dance sequence [$F_{(2,\ 57)} = 7.569$; $p = 0.001$; $\eta^2 = 0.210$] and how much they liked the music [$F_{(2,\ 57)} = 4.269$; $p = 0.019$; $\eta^2 = 0.130$]. No effects were found on how complex participants found the dance sequences to be [$F_{(2,\ 57)} = 0.337$; $p = 0.715$; $\eta^2 = 0.012$]. However, the training experience did not lead to the same effect across all questions. The biggest differences were observed between the physical performance and the auditory experience only group, with smaller or no effects seen between the physical training and audiovisual experience group (**Figure 5**). Compared to the auditory experience only group, participants in the physical training group show more positive responses after training to the questions about how much they like the rehearsed sequences ($p = 0.013$), how interesting they find the sequences ($p = 0.047$), and how much they like the music ($p = 0.019$).

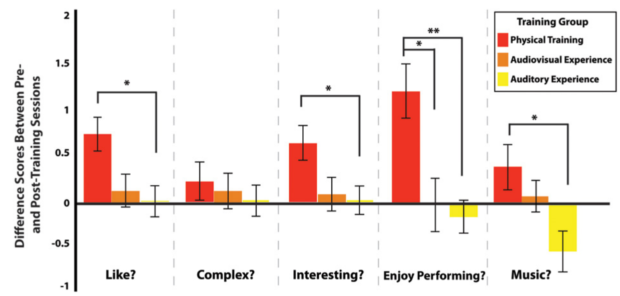

FIGURE 5 | Difference scores (calculated as post-training ratings - pre-training ratings) for each question, separated by training group. The single asterisk (*) denotes significance at $p < 0.05$ and the double asterisk (**) denotes significance at $p = 0.002$.

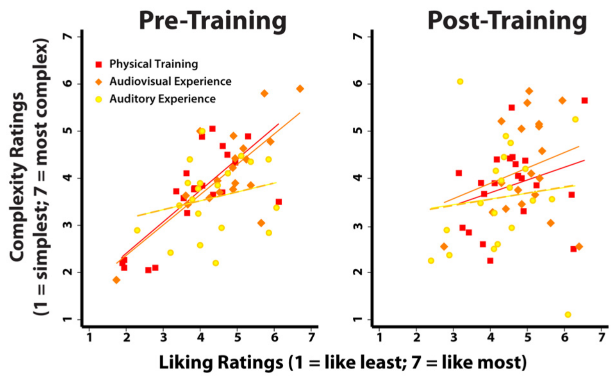

FIGURE 6 | Correlations between complexity and liking ratings, before and after training. The left plot illustrates the positive correlation between liking and complexity before participants had any kind of experience with the dance stimuli [similar to the situation in Cross et al. (2011)]. The lines represent the regression lines of the correlation for each group, pre- and post-training (see the Results section for r- and p-values). The right plot illustrates that the positive correlation evident for the Physical Training and the Audiovisual Experience groups disappears after several days of training, such that those movements that are viewed as most complex are no longer associated with consistently high liking ratings.

Moreover, after training, participants in the physical training group reported greater perceived enjoyment of performing the sequences compared to participants in the audiovisual experience groups ($p = 0.018$) and the auditory experience only group ($p = 0.002$).

To explore within-group effects of the training process on subjective evaluations of the dance sequences, we conducted independent MANOVAs for each training group testing for differences between pre- and post-training rating scores on the five questions. Any significant difference from zero (in the positive or negative direction) would suggest that the training procedures impacted perception. We found that participants from the physical training group significantly changed their judgments for four of the ratings [liking, $F_{(1, 19)} = 13.816$, $p = 0.001$; interest, $F_{(1, 19)} = 11.897$, $p = 0.003$; performance enjoyment, $F_{(1, 19)} = 16.279$, $p = 0.001$; and music liking $F_{(1, 19)} = 4.419$, $p = 0.049$]. In each of these instances, participants' ratings were significantly higher after training. No differences were seen between pre- and post-training ratings for participants in the audiovisual experience and the auditory experience only groups, with the exception that participants in the auditory experience only group liked the music less after training [$F_{(1, 19)} = 4.893$, $p = 0.039$].

The final analysis assessed whether a relationship existed between participants' ratings of liking and complexity for each movement, before and after training (**Figure 6**). When this analysis was run on pre-training scores, a significant correlation emerged showing that participants liked more those movements that they also rated as more complex ($r = 0.629$; $p < 0.001$). However, this positive correlation between liking and complexity disappeared in the post-training data ($r = 0.241$; $p = 0.066$). In order to better understand differences between the three training groups, we split the data into groups and ran the same correlations. The correlation between liking and complexity ratings was significant for the physical training and audiovisual experience groups (physical training group: $r = 0.755$; $p < 0.001$; audiovisual experience group: $r = 0.708$; $p < 0.001$), but not for the auditory experience only group ($r = 0.234$; $p = 0.320$). After training, the correlation was non-significant for all three groups. We ran an additional analysis to test whether the correlation coefficients differed before and after training, depending on group assignment (Raghunathan et al., 1996). We found a significant difference only for the physical training group and a marginally significant difference between pre- and post-training correlation values for the audiovisual experience group (physical training group: $z = 2.96$; $p = 0.003$; audiovisual experience group: $z = 1.98$; $p = 0.048$; auditory experience group: $z = 0.97$; $p = 0.3297$). This pattern of findings suggests that physical training most reliably impacts post-training ratings, while audiovisual experience alone has less of an influence on the relationship between liking and complexity ratings. The positive, pre-training correlation between complexity and liking is consistent with the behavioral data reported by Cross et al. (2011), and its disappearance after training will be considered in the discussion.

DISCUSSION

The primary aim of the present study was to investigate how different kinds of experience shape observers' aesthetic experience of watching dance. We were interested in whether increased experience with a dance sequence increases or decreases a spectator's enjoyment when watching that sequence. The hypothesis that increased familiarity is associated with increased liking (c.f., Jacobsen et al., 2006; Bohrn et al., 2013) was confirmed only for participants in the physical training group. Participants who physically practised dance sequences reported greater enjoyment when watching them, while no systematic differences in aesthetic ratings emerged among participants in the audiovisual experience or auditory experience only groups between pre-training and post-training sessions. This pattern of findings suggests that the experience of learning to embody an action may play a crucial role in how much pleasure one derives from watching that action.

On the first day of the study, we demonstrated a significant correlation between participants' ratings of liking and complexity before they had any kind of training with the movement stimuli.

Specifically, we saw that participants' ratings of liking positively correlated with their ratings of perceived complexity. Considering that participants had no prior experience with the movements on the first day of the experiment, we suggest that asking them to rate the complexity of a movement is comparable to asking them how well they could reproduce a movement (although we acknowledge that these questions are not tapping identical cognitive constructs). These findings are broadly consistent with the behavioral correlation between ratings of liking and reproducibility reported by Cross et al. (2011). Cross et al. (2011) found that participants preferred watching movements they perceived as most difficult to physically reproduce. One component that might modulate the link between complexity and reproducibility is how familiar one is with a particular movement. In both Cross et al. (2011) and the current study, participants were asked to passively watch and rate dance sequences, but participants in the study by Cross et al. (2011) watched and rated the sequences during a single experimental session (whilst undergoing fMRI). In contrast, participants in the current study watched and rated the sequences on two separate occasions separated by 4 days of training. This means that all participants in the current study were more familiar with the stimuli when making the post-training ratings. Additional empirical support for this theory comes from a recent study investigating aesthetic judgments of written texts (Bohrn et al., 2013). In this experiment, participants rated how much they enjoyed reading proverbs. The authors reported that participants' ratings of familiarity and beauty were positively correlated (Bohrn et al., 2013). The current results are in line with this finding, in that the participants who became most familiar with the stimuli (the physical training group) reported the highest liking ratings after training.

LIKING WHAT WE CAN DO: LINKS BETWEEN EMBODIMENT AND AESTHETICS

The data from the present study suggest that there is something specific about *physical* experience, *per se*, that leads to greater enjoyment of watching that movement. We can deduce this from the fact that participants in the audiovisual and auditory experience training groups did not report increased enjoyment when watching the movements after 4 days of experience, even though they spent an identical amount of time watching and/or listening to the music videos as those in the physical training group. Previous studies with non-dancers that have explicitly studied the aesthetics of watching dance have speculated that the link between increased sensorimotor neural activity and greater enjoyment is possibly due to an implicit desire within the viewer to embody the observed movement (Calvo-Merino et al., 2008; Cross et al., 2011). Freedberg and Gallese's (2007) embodied simulation account of aesthetics posits that a perceiver's aesthetic experience of a work of art is inextricably linked to the corporeal sensations evoked by the work. In support of this theory, Freedberg and Gallese focus exclusively on static works of art in the form of paintings and sculpture, and suggest that an observer can experience "embodied resonance" when viewing a piece of art based on the content of the work itself (such as the male form struggling to emerge from the marble in Michelangelo's *Slave Called Atlas*) or via the visible traces of the artistic medium (such as the wild scattering of paint in Jackson Pollock's *Number 14: Gray*). Freedberg and Gallese (2007) thus maintain that an observer cannot help but use his or her sensorimotor system when making aesthetic evaluations of artworks. Even though Freedberg and Gallese (2007) do not consider the art form of dance in their embodied simulation account of aesthetics, the findings from Calvo-Merino et al. (2008) and Cross et al. (2011) lend concrete support to this theory by demonstrating greater engagement of sensorimotor brain regions when watching movements rated as more aesthetically pleasing. The present findings provide additional support to this theory, as they are the first to show that an observer's aesthetic experience *increases* as a result of increased embodiment.

Another factor likely to have contributed to participants in the physical training group's higher aesthetic ratings post-training is a change in their perceptual fluency of observed movements. According to Reber et al. (2004), a key determinant of aesthetic pleasure is the perceiver's processing dynamics of a stimulus. In other words, the more fluently a perceiver can process a stimulus, the more positive their aesthetic response becomes. This idea has received support from research showing that observing or performing smooth reach and grasping movements toward everyday objects results in higher aesthetic ratings of those objects compared to objects that were grasped in a more awkward way (Hayes et al., 2008). In a recent paper, Montero suggested that dance training can facilitate the perception of certain aesthetic qualities of a dance, meaning that aspects such as grace, power, and precision may go unnoticed without any physical practice (Montero, 2012). A recent study from Calvo-Merino et al. (2010) has shown that motor training affects the way movement is perceived. The authors showed pairs of point-light displays of ballet steps to both ballet experts and non-experts, and found that experts were better at identifying which displays were identical and which were different, suggesting that experts' perceptual systems are finely tuned by extensive practice. Such a finding further corroborates Montero's idea (2012) that perceptuomotor experience greatly bolsters an observers' ability to evaluate or aesthetically judge dance movement. Thus, we argue that our findings are consistent with the notion that physical practice leads to increased perceptual fluency, and this in turn positively impacts aesthetic ratings. In the present study, only those participants who became physically familiar with the movements enjoyed watching them more post-training. One possible avenue for future inquiry is whether the relationship between perceptual fluency, experience and aesthetics might relate to an overarching notion of prediction error, such that we derive more pleasure from perceiving stimuli that are predictable (or familiar). While an expanding body of research explores questions of action predictability (and how experience shapes prediction processes; c.f., Diersch et al., 2012, 2013; Cross et al., 2013), to our knowledge this issue has not yet been explored in the realm of aesthetics or affective processing. We suggest that future work might be able to draw together these themes to better elucidate the relationship between familiarity, liking and predictability.

LIMITATIONS, IMPLICATIONS AND FUTURE DIRECTIONS

Several limitations of the current study warrant careful consideration. First, we acknowledge that the relationship between perceived movement complexity and liking requires further investigation and clarification. While we believe the correlation between liking and physical ability reported by Cross et al. (2011) is relevant to the correlation between liking and complexity reported in the present study, we still urge caution when considering both findings together. The present data show that complexity ratings did not change with training as much as liking ratings *increased* with training. Thus, it seems that physical familiarity engenders liking, but complexity is a more stable phenomenon that is less susceptible to change. We aim to further explore this relationship in future work.

Another aspect of the current study and other recent empirical work on dance aesthetics that could be refined is the method for evaluating the aesthetic experience of a dance observer. Although many researchers use the aesthetic rating dimensions of Berlyne (1974), we suggest that the development of more comprehensive or objective ways to measure aesthetic experience would be helpful. One possibility might be to adapt the implicit association test (c.f., Greenwald et al., 1998) as a means of sidestepping any kind of social (or artistic) desirability bias when assessing a work of art, while tapping participants' automatic appraisal of a stimulus. Ideally, any such new and improved measure of aesthetic appraisal would capture a more detailed and complete view of different perceivers' aesthetic evaluations, and could facilitate the comparison and matching of these personal, affective experiences to the underlying neural processes.

One issue to consider is whether empirical paradigms that study art-related stimuli in extremely reduced forms (such as the short dance clips used in the present study) are well suited to studying questions of aesthetics. Returning to the perceptual fluency points discussed in the previous section, it could be reasonably argued that aesthetic responses to the full dance sequences that participants perform or watch (or listen to) throughout the training week could be better interrogated through investigating responses to something more complete than 5–7 s segments of the dance movements. However, a number of studies have shown that fluency (and indeed, aesthetic) evaluations can be reliably surveyed with even very short movement stimuli in dance (e.g., Orgs et al., 2013) and non-dance (Cannon et al., 2010) domains.

However, this issue remains worthy of consideration and has not escaped the attention of other researchers whose work spans scientific and artistic domains. Jola et al. (2012b) have addressed this and related concerns through their discussion of how phenomenology and neuroscience are brought to bear on experiments involving dance as an art form. Through their work, they not only investigate observers' aesthetic responses via brain and behavioral measures during evening-length costumed dance performances in the theater (Jola et al., 2012a), but they also consider different ways in which dance and behavioral and brain science disciplines can be combined. On one hand, they point out how measures of cortical excitability during dance spectating can be used as measurement of engagement in dance (Jola et al., 2012b), but on the other hand they also argue for the additional benefit of qualitative interviews to investigate what participants actually liked and where they focused while watching dance performances. In their research, they found that people who enjoyed the dance performance gave answers that could be classified into the categories "desire to move," feeling a "connection to the dancer" and "having an emotional response to the performance." Their findings highlight how quantitative and qualitative research methods mutually inform one another and pave the way for developing new insights in the perception of dance.

Overall, the present study offers the next step to a better understanding of the influence of a spectator's prior experience with a movement on his or her aesthetic appraisal of that movement. We found that physical dance training led to increased ratings of enjoyment while watching dance. We have suggested several possible explanations for these results and how they inform earlier work in this field. The present findings advance the field of neuroaesthetics by giving a better understanding of the relationship between experience and the processing of stimuli (in this case, actions) by a human observer. Furthermore, by communicating this knowledge to the dance community and those involved in arts policy, these findings have the potential to aid in the development of arts outreach programs and new dance audiences. For instance, the first step in getting spectators more interested in watching dance might be to get them up and moving themselves.

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Autonomic nervous system correlates in movement observation and motor imagery

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The purpose of the current article is to provide a comprehensive overview of the literature offering a better understanding of the autonomic nervous system (ANS) correlates in motor imagery (MI) and movement observation. These are two high brain functions involving sensori-motor coupling, mediated by memory systems. How observing or mentally rehearsing a movement affect ANS activity has not been extensively investigated. The links between cognitive functions and ANS responses are not so obvious. We will first describe the organization of the ANS whose main purposes are controlling vital functions by maintaining the homeostasis of the organism and providing adaptive responses when changes occur either in the external or internal milieu. We will then review how scientific knowledge evolved, thus integrating recent findings related to ANS functioning, and show how these are linked to mental functions. In turn, we will describe how movement observation or MI may elicit physiological responses at the peripheral level of the autonomic effectors, thus eliciting autonomic correlates to cognitive activity. Key features of this paper are to draw a step-by step progression from the understanding of ANS physiology to its relationships with high mental processes such as movement observation or MI. We will further provide evidence that mental processes are co-programmed both at the somatic and autonomic levels of the central nervous system (CNS). We will thus detail how peripheral physiological responses may be analyzed to provide objective evidence that MI is actually performed. The main perspective is thus to consider that, during movement observation and MI, ANS activity is an objective witness of mental processes.

Keywords: motor imagery, movement observation, autonomic nervous system activity

INTRODUCTION

This paper aims to address Autonomic Nervous System (ANS) correlates of motor imagery (MI) and observation. More generally, we will focus on the more potential wide-ranging relationships between ANS activity and mental processes, required to perceive movement or to form a vivid mental representation of this movement. First, readers may question the association of this subpart of the nervous system with one of the highest human cognitive abilities. Indeed, the main well-known role of the ANS is to regulate vital functions of the organism (Appenzeller, 1990), whereas the observation and the mental representation of an action rely on cognitive brain functions (Jeannerod, 1997). The overall activity of the ANS is maintaining the homeostasis of the organism by adapting targeted physiological responses to both the demands of the internal milieu (e.g., postural changes or physical activity) and the changes in the environment (e.g., temperature, altitude, and microgravity).

While observing an action is a bottom-up process leading to perception, we define MI as a centrally controlled movement representation without any associated overt action. Observing a motor scene could thus lead to its mental representation and help the recall of memorized information. MI is mainly based on several sensory modalities, thus associating mentally evoked information (exteroceptive and proprioceptive) to those stored by the procedural long term memory (Decety and Grezes, 1999). According to Kosslyn (1988), two classes of processes are used to form mental images, ones that activate stored memories of the appearances of parts and one that arrange parts into the proper configuration.

Based on this first analysis, the question is "how could we establish a functional relationship between ANS functioning and the ability to observe and to mentally rehearse movements"? In other words, how mental processes, without any associated concomitant movement, could elicit ANS responses? One of the easiest ways to respond is to consider the preparation phase of an action. Anticipated cardio-vascular and respiratory adaptations are well-known physiological processes to face the forthcoming expenditure of energy. At the same time, one should recall the motor plan and adapt the execution parameters to the context in which the movement will be performed, i.e., among others, programming movement force, amplitude and direction (Paillard, 1982). We may hypothesize that, during this phase, we also recall the expected feedback usually provided by actual movement execution, both at the somesthetic (body sensations such as tactile or proprioceptive information) and the environmental levels (the effect of movement upon physical environment).

The idea developed by Grush (2004) is that in addition to simply engaging with the body and environment, the brain constructs neural circuits that act as models of the body and environment. If we specifically go back to the issue of performing a voluntary movement, we are in the presence of two seemingly decoupled processes, one quantitative aiming at providing energy for muscles, and one qualitative, designed to adapt parameters of movement execution to its goal (Näätänen, 1973).

Now, let us consider two different contexts within this preparation phase. In the first, the movement outcome is incidental, such as a free throw basketball brand in any end game while the team greatly leads. In the second case, the score is very tight and the success of the shot can allow the player to reverse the result and get his team in the lead. The same action within two different contexts will probably generate two different patterns of ANS responses. Thus, the ANS reacts not only when energy is required to perform an action but also when emotional significance is associated with the action. Therefore, there is a first link between physiological responses from the ANS and mental processes, evidenced through the implicit knowledge of action consequences in case of success or failure. Such consequences may be considered because they can be mentally evoked. From this preliminary observation we can emphasize that each mental construct leading to the building of motor representation should be associated with specific ANS patterns (Decety et al., 1991; Decety, 1996; Guillot and Collet, 2005; Collet et al., 2011).

Based on the classic designs of ANS physiology, we will then describe how the scientific relations between mental processes and the ANS were developed. More precisely, we aim to decipher the reciprocal influence between mental processes, i.e., MI and observation, and ANS activity. In particular, we will describe the ANS responses associated with bottom-up processes (sensory intake operations) and address this issue through the illustration of movement observation. The rejection operation rather corresponds to MI as we could hypothesize the existence of a top-down mechanism, based on the activation of the central representation of movements stored by the procedural memory. In turn, the activation of peripheral effectors during MI also seems to be centrally controlled and we will address the issue of simultaneous programming of somatic and vegetative effectors by common central structures (Collet and Guillot, 2009, 2010). Therefore, we will demonstrate that the ANS correlates of observation and MI offer better understanding of the main features of movement representation. Among others, we will then focus on cardiac and electrodermal activity (EDA) with the aim to detail the main features of these physiological variables, easily recordable with unintrusive procedures. We will progressively examine how mental functions may elicit physiological responses at the peripheral level of the autonomic effectors and illustrate our statements by several examples taken from different fields of human activities, such as usual actions, sporting skills, or motor recovery.

HOW THE AUTONOMIC NERVOUS SYSTEM FUNCTIONING IS USUALLY DESCRIBED?

In this chapter, we will first review the traditional conceptions related to ANS functioning and describe how the evolution of knowledge has enabled the consideration of ANS activity as a witness of cognitive processes. Early understanding about ANS functioning helps to appreciate why ANS activity was disconnected from other functions than those ensuring the maintenance of vital functions through homeostasis.

It is logical to consider that the control of vital parameters is under automated processes, inaccessible to consciousness, and that physiological variations associated with these vital functions remain unrelated to high mental processes. The ANS is composed of visceral afferent pathways, integration centers at the level of the medulla, the brain stem, the hypothalamus and cerebral cortices. The organization of the ANS describes different efferent pathways subdivided into sympathetic, parasympathetic and enteric branches (Appenzeller, 1990) responsible for regulating internal organs function by nervous signals and neurotransmitters releasing (McCorry, 2007). For example, the medulla has been described as the source for basal vasomotor tone for over 100 years (Hilton, 1981). Efferent pathways target internal organs and, in particular, the cardiac muscle, the smooth muscles, as well as the exocrine and endocrine glands. An important point which will be further developed is that these efferent pathways also innerve the skin directly at the interface between the body and the environment. The ANS is also made of afferent pathways, organized in two sub-systems, the oligosynaptic circuits mediating reflex adaptation responses of the visceral systems, and more complex circuits with projections to nuclei in the brain stem and the brain. Information is collected at the level of internal organs and transmitted to the nervous structures which thus receive feedback information from the periphery. For example, the regulation of the heart and peripheral circulation is under the control of centers in the medulla that receive descending input from higher neural areas in the brain and afferent input from mechanically and chemically sensitive receptors located throughout the body (Mitchell and Victor, 1996). Taken together, this basic view leads to a self-regulating system including centers of commands governing peripheral effectors and feedback information regulating the original command. Functionally, the ANS is made of two main sub-systems, the orthosympathetic branch designed to mobilize energy to face emergency situations (catabolic function), and the parasympathetic branch with the opposite function, i.e., restoring and maintaining the resources of the organism at a level compatible with life functions (anabolic function)[1]. This organization is still valid in light of the advances of modern physiology but remains objectionable for, at least, two main reasons:

(1) From an anatomical viewpoint, and with reference to Xavier Bichat (1802), the ANS remains considered a part of the peripheral nervous system, despite well-identified centers within the spinal cord, the brainstem, the diencephalon and cortical areas (Loewy and Spyer, 1990; Saper, 2002). The two subdivisions made to better understand the organization of the nervous system led Bichat to artificially separate the continuous action of

[1]The enteric nervous system whose we previously referred to, consists of a mesh-like system of neurons that governs the function of the gastrointestinal system. It will not be described further here because the variables indicating its activity cannot be measured by non-intrusive procedures.

the part controlling "*the organic life*" (visceral) and the intermittent action of the other controlling "*the animal life*" (somatic). In other words, the will and the consciousness leading to voluntary actions in relation with the environment are non-ambiguously separated from self-regulating functions of energy supply, control of energy spending and system maintenance.

(2) From a functional viewpoint, the ANS is designed to maintain constant the internal milieu by mean and opposing reciprocal actions of the sympathetic and the parasympathetic branches (Cannon, 1929). As traditionally described, the sympathetic system has a chain of interconnected ganglia close to the spinal cord, each specifically connecting pre-ganglion to post-ganglion fibers, thus sending information to the target organs. Consequently, the information was believed as being spread across the ganglia chain, resulting in overall activation of the organism thus eliciting the well-known sympathetic tone. Although this concept remains valid and well-accepted (Calaresu and Yardley, 1988), we will later see that this old conception must be qualified. The sympathetic function has thus been described as serving the mobilization of bodily resources, e.g., increasing cardiac and respiratory frequencies facilitating oxygen uptake, routing blood from internal organs to somatic muscles in case of movement preparation and execution, thus providing supplementary energy to both brain and muscles. Conversely, the parasympathetic branch function is mainly anabolic and is likely to decrease demands in energy, e.g., bringing the heart rate to basal level[2].

Hence, the two subsystems of the ANS have been described as being functionally opposite but with complementary organizations, the action of one branch being reciprocally inhibited by the other, depending on the energy supply for each vital function. ANS functioning was thus summarized as the collaboration of two antagonist subsystems, leading to the image of equilibrium between the two and to the concept of sympatho-vagal balance. Despite powerful clinical application in the field of sudden death prevention (cardiovascular risk stratification) through the heart rate variability (HRV) analysis (Pieper and Hammill, 1995; Malliani and Montano, 2002; Montano et al., 2009), this organization needs update.

NEW CONCEPTS IN NEUROVEGETATIVE PHYSIOLOGY

During the last 20 years of the XXth and the early years of the XXIth century, advances in neurovegetative physiology led to question the old conceptions related to ANS functioning. It is not simply organized, i.e., only playing the role of a quantitative system mobilizing energy to serve behavioral output. Two fundamental notions have been more specifically highlighted and discussed independently.

ABOUT THE SYMPATHETIC TONE

The well-accepted notion of sympathetic tone (Calaresu and Yardley, 1988) was early questioned on by the teams of Wallin (1981). They were probably among the first to develop a method enabling the recordings of sympathetic nerve activity targeted to the skeletal muscle vasculature with intra-neural microelectrodes. This technique provided a powerful new tool to study fundamental mechanisms of neuro-circulatory regulation in conscious human participants. During the last three decades, micro-neurographic studies have shed new light on the reflex regulation of skeletal muscle sympathetic nerve activity by arterial baroreceptors, arterial chemoreceptors, and cardiopulmonary baroreceptors (Mitchell and Victor, 1996). Direct recordings of the neural sympathetic activity showed specific responses with little cross talk between ganglia. This finding was later confirmed by Wallin and Fagius (1986) for the experimental article and Wallin and Fagius (1988) for the review article, who found that muscle endings are sensitive to variation in blood pressure while skin endings remain silent. Conversely, the sympathetic endings innervating the skin are very sensitive to mental stress, whereas those innervating muscles are not. A series of experiments by Vissing (1997) further provided evidence in support of a selective central motor command, and demonstrated a highly dissociated pattern of sympathetic activation to skin and skeletal muscle. This set of results is in favor of separated subsystems within the sympathetic organization, made of building blocks controlling specific internal functions (Jänig, 1988). Jänig, McLachlan and Häbler confirmed these first results and synthesized the main data within a series of review papers between 1992 and 2003. Though the sympathetic component of the ANS is widely concerned with the body response to stress, they demonstrated that a range of neuroscientific techniques (including micro-neurography, see Vallbo et al., 2004 for a review) revealed the specialized properties of the functional pathways in the sympathetic system at molecular, cellular and integrative levels (Jänig and McLachlan, 1992a,b; Jänig and Häbler, 1999, 2003). Interestingly, these results confirmed that ANS activity was specifically modulated by mental processes such as mental stress (Vallbo et al., 2004). The emergency function of the ANS was thus incorporated into the general concept of stress or arousal. For example, after stressing the participant with a loud noise, direct measurements of muscle sympathetic nerve activity showed a decrease of bursts. Skin sympathetic activity also increased at the onset of static exercise before any rise in direct measurements of muscle sympathetic nerve activity. Thus, during experimental conditions different from rest (e.g., mental stress and exercise), specific changes in sympathetic activity to selected tissues (e.g., skin) occurred while there was no change at the level of others (e.g., muscle). In addition, inter-individual differences were reported in sympathetic responses to arousal (Halliwill et al., 1997; Donadio et al., 2002) and to mental stress (Carter and Ray, 2009). The hypothesis of selective influence of sympathetic outflows was also shared by Kummer (1992), and more recently by Morrison (2001). Let the concluding sentence to Vallbo et al. (2004):

> "The early views of the sympathetic nervous system as a monolithic effector activated globally in situations requiring a rapid and aggressive response to life-threatening danger have been eclipsed by an organizational model featuring an extensive array of functionally specific output channels that can be simultaneously activated or inhibited in combinations that result in the patterns of autonomic activity supporting behavior".

[2]The organization of the ANS is well described in textbooks of general physiology. For a more detailed description, see Appenzeller (1990) " The autonomic Nervous System ", pages 3 to 7, Figures 1–6 of Chapter 1 (Anatomy and histology). See also Thayer et al. (2009) for an detailed description of the relationships between central autonomic nervous system centers within the brain.

In a series of original publications from 1995 to 2009, Porges underlined that early conceptualization of the vagal function, focused on an undifferentiated efferent pathways, was assumed to modulate "tone" concurrently to several target organs (Porges, 2009).

THE VAGAL PATHWAYS

Interestingly, Porges reported how the internal organization of the vagal pathways changed across phylogenetic transitions in the vertebrates ANS. Specific changes in vagal pathways regulating the heart occurred along the phylogenetic shift between reptiles and mammals. At the neurological level, heart regulation shifted from the dorsal motor nucleus of the vagus in reptiles to the nucleus ambiguous in mammals, leading to two subsystems within the main parasympathetic branch. The fibers originated from the dorsal motor nucleus of the vagus are unmyelinated (dorsal vagal complex) while those from the nucleus ambiguous are myelinated (ventral vagal complex). Interestingly, the first subsystem is the part of the vegetative vagal function *per se*, thus acting as a behavioral moderator, while the second is mostly linked with more attention processes, emotional reactivity and social communication (Porges, 2007a). Thus, Porges drew the same conclusion to that we reported when describing the organization of sympathetic pathways. The Porges' polyvagal theory links the evolution of the ANS to affective experience, emotional expression, facial gestures, vocal communication, and social behavior. There is thus a clear linkage between mental functions and the ANS (Porges, 1995a).

SYMPATHETIC AND PARASYMPATHETIC RELATIONSHIPS

Finally, Berntson et al. (1991) reported that the relationships between the two ANS subsystems are more complex than the principle of simple reciprocity. They showed that coupled reciprocity is only one of eight possible "modes of autonomic control" that determine heart rate. As reported by Backs (1998), faster heart rate could be elicited by multiple autonomic control modes, e.g., reciprocal coupling, or other modes of autonomic control such as uncoupled sympathetic activation or uncoupled parasympathetic inhibition. We could also assume that autonomic activity may change greatly even when heart rate does not vary across tasks with non-reciprocally coupled control modes such as sympathetic and parasympathetic co-activation or co-inhibition. For example, Grossman et al. (1990) reported that mental arithmetic elicited reciprocally coupled sympathetic activation and parasympathetic inhibition, whereas negative emotion-induction elicited sympathetic and parasympathetic co-activation, however with a larger sympathetic than parasympathetic response. This interesting approach to cardiac physiology and its relationships to mental processes experienced a period of intense production in the 1990's and then gradually dried up. Methods to delineate the respective contribution of each system were progressively oriented toward more integrated and more sophisticated treatments of cardiac activity, specifically HRV through temporal, frequential (power spectrum) or non-linear analysis. HRV is the beat-to-beat variability of heart rate and is under the main control of the parasympathetic system as the sympathetic outflow on the heart is too slow to elicit beat-to-beat changes (Jose and Collison, 1970). HRV is probably the most used index to assess vagal activity. HRV is sensitive to physical exercise and decreases with increased exertion (Yamamoto et al., 1991). Interestingly, it has been shown that HRV was also sensitive to mental load and, more generally, to any kind of stressor (see Porges, 2007b; Thayer et al., 2009, 2012, for extensive reviews). In this context, HRV has been related to the activity of the prefrontal cortex (Lane et al., 2009), a set of neural structures controlling cognitive performance. More precisely, the model of neurovisceral integration (Thayer and Lane, 2000; Thayer et al., 2009) details the pathways regulating the cardiovascular system from the frontal cortex and describes how these networks associating cortical, sub-cortical and limbic structures control cognitive performance and executive functions with HRV as the main dependent variable. For example, the vagal activity was indexed by and associated with the functioning of selective attention under load by Park et al. (2013).

> This issue was early hypothesized by Hugdahl (1996) who concluded that Autonomic activity that accompanies attention, orienting and learning has demonstrated that the ANS is not simply a "non-cognitive" and automatic part of brain function thus linking the study of mental processes to non-ambiguous and easily measurable changes in ANS activity.

BOTTOM-UP AND TOP-DOWN MECHANISMS

One of the first experimental proofs of such a linkage probably originated from the early studies of the well-known orienting response defined as the simultaneous response of both the somatic and the ANS to specific stimuli. Appropriate sensory receptors record specific properties of the stimulus which then result in orienting the body into the direction where this stimulus originated (bottom-up). Simultaneously to orienting behavior, alertness increased, thus eliciting a sympathetic response, e.g., increased heart rate or EDA. Both somatic and autonomic activities thus attest that the individual perceived the stimulus. Interestingly, Sokolov et al. (1963) associated the orienting response to the representations of the world in memory thus suggesting that the mental evocation of the same information without its physical presence could generate the same physiological responses (top-down). Due to its role in alertness, the ANS is very sensitive to stimulus novelty which is better aimed at eliciting strong ANS responses e.g., increased heart rate and blow pressure (LeDoux, 2000), simultaneously with different bodily reactions ("flight or fight" responses). Information to which the individual has often faced would obviously elicit weaker responses or no response due to habituation (Bradley, 2009). If this information is memorized, it is likely to be rapidly recognized during observation by the perceptual function which directly compares its actual features to those previously stored by memory during past experiences. The next step is to consider that any memorized information could be recalled in the absence of any overt stimulus, i.e., mentally evoked as mental image. Finally, we may hypothesize that any information mentally evoked could elicit the same ANS activity than that elicited under actual conditions, i.e., during the observation of actual information. The two processes nevertheless differ as the first results from a bottom-up process while the second further depends on a top-down process. An intermediate phase would suggest that behavioral and physiological responses could be indirectly elicited by pre-cued information. If the presentation of partial information could lead to the recognition of the full information, thus observing pictures or videos is likely to evoke the equivalent mental material stored in memory thus helping the construction of mental representation. The evocation of the movement by viewing the motor scene would probably elicit the same mental state, and thus the same physiological changes as those usually obtained when actually performing the action (Paccalin and Jeannerod, 2000; Bolliet et al., 2005b).

HUMAN MENTAL PROCESSES AND THE AUTONOMIC NERVOUS SYSTEM

At this stage, we assume that both external stimuli, e.g., observing somebody performing a motor sequence, and internal stimuli like mentally rehearsing an action could elicit ANS responses. A particular class of movements is that related to the activity of face muscles when feeling an emotion or when observing somebody feeling an emotion. These could be accompanied by motor activity of the whole body depending upon the intensity of the feeling.

EMOTION AND THE ANS

Ekman et al. (1983) early showed that heart rate increased when professional actors observed faces miming each basic emotion non-ambiguously. Specific increase in skin temperature was also recorded when the actors mimed this emotion simultaneously with the observation of an individual feeling anger. Direct recordings from postganglionic sympathetic axons innervating the skin with intraneural microelectrodes confirmed that skin sympathetic nerve activity increased with the observation of both positive and negative emotional images (Brown et al., 2012). The observer can then mentally imagine somebody else feeling the same emotion as that previously observed (external MI). He or she can also imagine him (her) feeling this emotion (internal MI). By applying this reasoning to human movement, we thus delineate four mental processes likely to elicit simultaneous changes in ANS activity:

(1) Observation of somebody actually performing a movement or through a video scene (third-person perspective[3]).
(2) Observation of self in the process of performing an action through a video (first-person perspective).
(3) Representation of somebody performing a movement with previous stimulus induction (or not) with a video (third-person perspective).
(4) Representation of self in the process of performing the same motor sequence, without any external pre-cueing to help MI. In this latter case, the mental image is self-triggered and supposed to be associated with specific ANS responses.

[3]We previously referred to internal and external MI. It is also usual to distinguish between two MI perspectives, i.e., the spatial perspective from which MI is performed. The first-person perspective is the representation as an actor during which we imagine ourselves performing the movement. The third-person perspective is the representation as a spectator during which we imagine someone else or ourself performing the movement.

Many experimental findings indicate that the observation or the mental representation of emotional events activate the ANS, probably from the amygdala (LeDoux et al., 1988). The amygdala's lateral nucleus receives and integrates the sensory inputs from sensory systems which relay in the thalamic and cortical areas. The central nucleus provides the interface with motor systems controlling specific fear responses in various modalities, including behavioral, autonomic, and endocrine responses. Thus, observing or imagining emotionally significant objects or scenes has identical bodily effects as actually seeing the same objects or scenes. Lang et al. (1993) reported an increase in skin conductance, as well as in heart and breathing rates, when participants viewed pictures of threatening objects. Interestingly, the same changes occurred when the participants visualized these objects. To add to this finding, Kosslyn et al. (1996) found that mental images of aversive stimuli activated the anterior insula, one of the major cortical sites controlling EDA and feedback from the ANS, while Kreiman et al. (2000) recorded increased activity from single cells of the hippocampus, amygdala, enthorinal cortex and parahippocampal gyrus when participants looked at pictures or formed mental images of these pictures. Therefore, some of the cells responding selectively when participants viewed emotionally significant stimuli were also selectively active when they were asked to imagine the same stimuli. Thus, imagery might engage neural structures also involved in perception (for a more exhaustive review, see Kosslyn et al., 2010). This statement is congruent with clinical data, where parallel deficits in imagery and perception were reported (Farah, 1984; De Vreese, 1991; Young et al., 1994). In turn, these neural structures may affect peripheral effectors of the body itself, e.g., heart rate or EDA modulation.

OBSERVATION, ATTENTION AND THE ANS

Paccalin and Jeannerod (2000) reported consistent changes during two experiments where participants actually watched an actor lifting a weight with increasing loads or a walking and running performance on a treadmill moving at increasing speed. Accordingly, changes in respiration rate of the observer were proportional to the effort made by the actor and followed the actor's running speed, especially during accelerated running. The respiration rate also increased linearly with the treadmill speed. These results provided first evidence of ANS correlates during the observation of a motor sequence. Bolliet et al. (2005b) then compared two experimental conditions including the observation of a video sequence of oneself and that of somebody else performing the same movement. While the observation elicited ANS responses different from those recorded at rest, no difference emerged among ANS responses of actual movement execution, self-videotaped observation and video-taped observation of somebody else performing the same movement. The same issue was recently addressed by Brown et al. (2013) who requested the participants to watch a first-person running video, i.e., viewing the action as if they had a camera on their own head. They observed significant increases in heart rate, respiration rate, skin blood flow and burst amplitude of muscle sympathetic nerve activity by comparison with baseline. They did not, however, compare the first-person to the third-person perspective. It could be hypothesized that watching a first-person could lead to more engaged observation that watching a video from a third perspective and therefore evoke stronger ANS activity. Nevertheless, both studies by Bolliet et al. (2005b) and Brown et al. (2013) bring a first argument showing that perception, observation and action share common mental processes (Jeannerod, 2001). Decety et al. (1991) early evidenced that self-representation of walking was subjected to elicit ANS responses. Heart rate and pulmonary ventilation covaried with the degree of mental effort, during the mental simulation of locomotion. This was further confirmed by Papadelis et al. (2007) who revealed that heart rate and respiratory frequency significantly increased during imagery sessions as compared to rest. As a whole, these data suggest that the cognitive processes activated during movement execution are involved to the same extent during movement observation and MI, whatever the experimental condition. Another interesting issue is that the ANS responses were proportional to the mental effort. It was generally weaker when the observed movement was performed with low intensity compared to high intensity. For example, lifting a load of about 50% of own best mark elicited smaller and shorter ANS responses than when lifting a load of 90% of own best mark.

Observation seems obviously linked to attention since we must orient our sensory systems (in particular the visual system) in the direction of information of particular interest and then focus our attention while inhibiting concurrent activities which may be seen as distractors. Rizzolatti et al. (1987) early linked the orienting of attention with ocular movements programming, i.e., the attention needed to observe a given event is adequately oriented when the oculomotor program for moving gaze toward this event is ready to be executed. Publications focusing on central correlates of motor observation have been a resounding success since the discovery of mirror neurons by Rizzolatti et al. (1996). Many articles have been added to the first data from the years 2000 and more than one hundred review papers have been published since the first review by Rizzolatti et al. (1999). More precisely, the ventrolateral premotor cortex and the anterior part of the intraparietal sulcus are strongly activated during the observation of actions in humans (Manthey et al., 2003). Another interesting issue deals with the role of the ventral premotor cortex responding to the observation of mouth actions in language comprehension and hand movements associated with language. This is due to the fact that Broca's area, mediating language production and comprehension in the dominant cerebral hemisphere overlaps, in part, with the human ventral premotor cortex (Binkofski and Buccino, 2006). Therefore, the observation of actions performed with the hands and the mouth both activate the ventral premotor cortex and Broca's area. Functionally this complex network is probably involved in polymodal action processing. This execution—observation matching system is a part of polymodal action recognition system, associated with language processing, thus facilitating communication among humans through verbal and motor messages (see Fiebach and Schubotz, 2006, for a more extensive review of the functional contribution of the ventral premotor cortex and adjacent Broca's area to perceptual, cognitive and motor processing). This redundancy within the central nervous system (CNS) is likely to favor clear and unambiguous communication among peers of the same species. Thus, this central organization should be paralleled by peripheral activity both at the level of the somatic (facial expressions and general body language) and the ANS (variations of heart and respiratory rates, selective vasoconstriction or vasodilatation).

As previously mentioned, these mental processes are likely to elicit the same ANS activity as during actual behavior. This nevertheless remains a working hypothesis which should be tested by specific experimental paradigms. As the observation of movements was early shown to modulate premotor cortex activation (Rizzolatti et al., 1996; Manthey et al., 2003), we could infer that physiological activity should be recorded at the level of autonomic effectors. We could nevertheless hypothesize that these responses should be related to the significance attributed to the observed actions. In the first experiments on monkeys by Rizzolatti et al. (1996), the observation of usual daily activities (observation a peer grasping food, then bringing it to mouth) triggered the activity of the rostral part of monkey ventral premotor cortex (area F5). Interestingly the authors also observed that F5 area remained silent when the food was handled and grasped with a tool whose function was unknown by the monkey. Therefore, the activity of this area is also linked to the meaning attributed to the observed action. Manthey et al. (2003) further underlined that neural activity within this area was also modulated when observing erroneous and senseless actions. While the purpose of this paper was to distinguish brain activations corresponding to the analysis of movements from those related to objects during the observation of actions, we could nevertheless underline that neural activity varies when the observed action makes sense or not, or when the action is not well goal-directed. Several working hypotheses could be drawn considering ANS responses that we might expect to correlate to movement observation, taking its meaning into account. The observation of a movement making no sense would then elicit a strong ANS response corresponding to general alertness which would nevertheless be highly and quickly sensitive to habituation. On the other hand, the observation of a movement stored in memory would elicit longer ANS responses duration due to the time needed for action recognition and its emotional significance. Autonomic markers of action observation thus need further experimental investigations to be better described and understood.

Contrasting with the proliferation of work about the CNS correlates in movement observation, articles dealing with the ANS correlates have been limited and did not receive much attention from the scientific community. Observation is probably based on a process connecting the observed movement onto an internal model of the same movement that could then make the participant simulating that action (Iacoboni et al., 1999). In turn, a simulated action can elicit perceptual activity which resembles the activity that would have occurred if the action had actually been performed (Hesslow, 2002). According to Nyberg et al. (2000), different perceptual activities can elicit perceptual simulations, including observation due to its ability to emulate mental representation of movement simultaneously with its observation (see also Macuga and Frey, 2012). With reference to these theoretical and empirical contributions, we may conclude that perception, observation and mental representation share many common mental processes mainly based upon sensorial perception and information stored by the memory systems (Jeannerod, 2001).

As far as motor action is considered, MI should elicit the same central and autonomic activities as those recorded when the movement is actually performed. There are many examples of central activations by MI in the scientific literature (for review, see Guillot et al., 2012). Ehrsson et al. (2003) nicely showed how MI of voluntary movements of several body segments activated the corresponding body-part-specific motor representations (see also Michelon et al., 2006; Szameitat et al., 2007a,b). Comparing brain activations of actual and imagined movements leads to better understand the process of forming mental representations (Among others, see Hanakawa et al., 2003, 2008; Lotze and Halsband, 2006; Munzert et al., 2009). Meister et al. (2004) reported that actually and mentally playing music on a silent keyboard yielded similar activation of the fronto-parietal network. The matching of brain activation during actual execution and MI is a reliable mean to evaluate the quality of mental representation (Lebon et al., 2012). These data provide arguments in favor of the functional equivalence between a movement and its mental representation (Jeannerod, 1994; Grezes and Decety, 2001).

THE AUTONOMIC NERVOUS SYSTEM: A WITNESS OF MOVEMENT OBSERVATION AND MI

MI is usually defined as a dynamic mental state during which the representation of a given motor act is internally rehearsed in working memory without any overt motor output (Decety, 1996). MI is born from self-mental activity and anyone can generate a mental image by recalling any motor program stored by procedural memory. Unlike observation, MI originates from an internal model, resulting from mental operations of generating sequential actions without any overt movement[4] (Wolpert and Flanagan, 2001; Davidson and Wolpert, 2005). Thus, the mental image is self-formed and the individual does not necessarily need any external information to generate the representation of an action, i.e., a kind of pre-cueing which could help its construction. More precisely, MI is a mental construct, "*a class of images of one's own bodily movements which are used to simulate or plan for subsequent action*" (Stevens, 2005). Therefore, defining MI in these terms underlines the close relationship between movement representation and motor preparation and prefigures the links that could be established between MI and ANS activity. As previously described, the CNS prepares the motor command while the ANS provides the metabolic resources necessary for its execution (Mogenson, 1977). Motor skills require being planned and programmed before the actualization of these operations leads to motor commands and actual execution (Paillard, 1982). If this is an obvious function of the CNS, motor preparation also involves the ANS for providing resources in energy that makes movement execution possible.

A SPECIFIC INDEX OF THE SYMPATHETIC SYSTEM: ELECTRODERMAL ACTIVITY

Among others, EDA was early believed as being closely related to mental states. EDA is one of the oldest physiological indices, early recorded at the end of the XIXth century. Féré (1888) and Tarchanoff (1890) believed that EDA was likely to provide information about mental states. Measuring skin conductance or skin resistance (one being the reverse of the other) is of particular interest since EDA variations result from the activity of the eccrine sweat glands which are only controlled by sympathetic endings through acetylcholine release (Shields et al., 1987). The innervation of sweat glands is thus an exception to the principle of dual innervations. There is no parasympathetic command to sweat glands, certainly because stopping sweating simply occurs when the sympathetic command stops itself. Interestingly, EDA is a direct witness of sympathetic action through sweat release, mainly at the level of palmar and plantar surfaces. Thus, EDA reflects the general arousal of an organism and changes in arousal in response to emotionally significant stimuli from both the individual him (her)self or from the environment. Increased arousal is correlated with skin conductance[5] increase or skin resistance decrease and is paralleled by cardiovascular changes, e.g., increases in heart rate and blood pressure, decrease in HRV. All these physiological changes give evidence of energy mobilization for the preparation of movement execution.

Motor preparation and movement execution are generally associated with EDA increase (Critchley, 2002). These motor-related autonomic responses are mediated, in part, by commands from the CNS, which make the sympathetic arousal varying, according to information significance. As early supposed by Edelberg (1972), results by Vissing et al. (1991), Vissing and Hjortsø (1996), and Vissing (1997) confirmed that sympathetic activation of skin is predominantly influenced by central motor commands (**Figure 1**). By recording sympathetic nerve activity with microelectrodes placed selectively in skin and muscles during isometric hand contractions, they reported that:

(1) Static exercise markedly increases sympathetic outflow to skin as well as to skeletal muscle.
(2) The increase in skin sympathetic nerve activity, unlike muscle sympathetic nerve activity, appears to be caused mainly by central command rather than by muscle afferent reflexes.
(3) This sympathetic activation of the skin appears to be targeted both to sweat glands and vascular smooth muscle.

At the anatomical level, we thus have several proofs of connection between the CNS and the ANS during the execution of voluntary movements. At the functional level, somatic motor commands are paralleled by a series of autonomic commands targeting skin effectors, i.e., sweat glands and smooth muscles of blood vessels. The resulting effect was to elicit EDA as well as skin blood flow decrease due to skin blood vessels constriction. Thus, EDA may be seen as a sensitive psychophysiological index of changes in autonomic sympathetic arousal that are integrated with sensory-motor, emotional and cognitive states. As previously described, EDA correlates of actual motor command should also be elicited when a motor sequence is simply observed or mentally evoked, i.e., when the participant visualizes the sequences of movements

[4]A clinical case study showed that brain injury has removed the dissociation between actual performance and mental representation, the patient being no longer capable to inhibit the execution of the movement he was imagining (Schwoebel et al., 2002).

[5]Without specific information, we refer to skin conductance as an index of electrodermal activity.

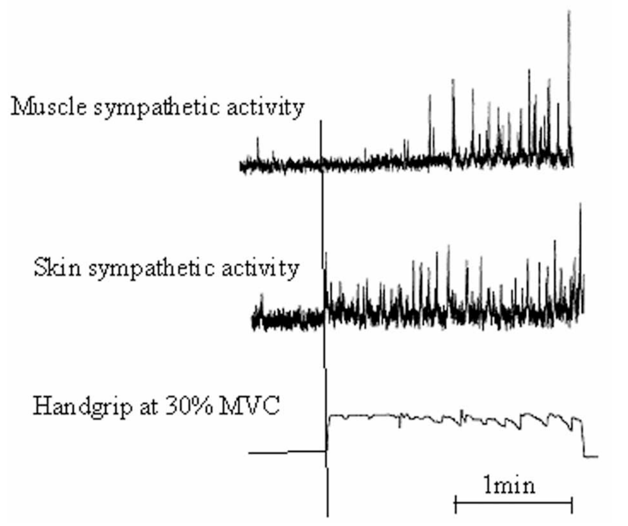

FIGURE 1 | Illustrative recording from a participant showing a 2-min sequence of static handgrip at 30% maximal voluntary contraction [Adapted with permission from Vissing et al. (1991), Circulation Research]. Muscle and skin sympathetic nerve activity are recorded from left and right peroneal nerves. Static handgrip markedly increased both skin and muscle sympathetic nerve activity. However, skin ANS increased rapidly and anticipated the onset of handgrip, whereas muscle ANS increased much more slowly with a latency of almost 1 min from the onset of handgrip to the onset of sympathetic activation.

and/or perceives the corresponding body sensations usually. For instance, Oishi et al. (2000) and Oishi and Maeshima (2004) reported a significant decrease in skin resistance associated with increase in heart and respiration rates as early as participants started a MI session, compared to the control condition.

The ANS has features that make this system the natural "first principle" from which initiation of action can arise (Peters, 2000). To give proofs to this assumption, we will first describe how ANS activity is analysed to differentiate a mental state from rest, on the one hand (Falk et al., 2010), and to detect motion execution with a distinction among several movements, on the other (Marchal-Crespo et al., 2013). In the first experiment, Falk et al. (2010) recorded several ANS variables (EDA, skin temperature, heart rate and respiration rate) then processed with hidden Markov models[6] to automatically detect whether a participant was subjected to perform music imagery as opposed to rest. In the second experiment, Marchal-Crespo et al. (2013) aimed at detecting motion execution by monitoring ANS responses. They first selected a series of four ANS variables which were also processed with the hidden Markov models. The participants were requested to perform several discrete isometric pinching sequences with the aim to detect the pinching periods from rest. Movement execution was accurately classified and separated from rest on the basis of peripheral autonomic signals. Accuracy, sensitivity and specificity reached level of significance. This methodology gives promising evidence for further research on the use of the ANS response in body-machine interfaces.

ANS RECORDINGS AND BRAIN-COMPUTER INTERFACE

When severe and multiple disabilities of the somatic part of the nervous system do not allow individuals to have an access pathway to interface with their environment, controlling the self-regulation of central signals of the ANS may provide a reliable substitute. Peripheral ANS signals can be voluntarily triggered and associated with a brain interface, thus having the potential to be used as an access pathway by the target population (Blain et al., 2008). Body-machine interface may help people suffering from neurological injuries to assist the movement they cannot achieve by themselves. Central signals from MI activity as well as their peripheral correlates, in the form of a set of ANS responses, may be associated to allow participants attempting to trigger robotic assistance. In turn, active assisted exercise provides novel somatosensory stimulation that can help induce brain plasticity (for reviews, see Dobkin, 1993; Rossini and Pauri, 2000; Rossini and Dal Forno, 2004; Dunlop, 2008). Brain-computer interfaces could be designed to control robotic devices which may help to move the impaired limb with the condition that either an intention to move is detected from cortical activity. The physiological change associated with the intention to move should be emphasized if this signal is associated with additional cortical activity generated by MI. Finally, both signals from the CNS system could be linked to peripheral ANS responses these are likely to elicit. Thus, the feasibility of a body-machine interface aimed at detecting motion execution may rely on monitoring the ANS response, an easy and unintrusive method to detect physiological signs from the will. The question of whether specific physiological signs (such as electrodermal responses) are reliable remains open as these can be severely impaired in the event of spinal cord injury, for example. The spinal cord isolated from the brain stem has less or no potential to generate electrodermal responses, as supraspinal connections are necessary for this. More precisely, the integrity of central sympathetic pathways of the upper thoracic segments is required for palmar electrodermal responses and possibly all thoracic segments for plantar electrodermal responses (Yokota et al., 1991; Cariga et al., 2002). If the electrodermal responses are too different due to the variability of spinal cord lesions, the control of a brain-machine interface would be too random. This means that associating several physiological signs together would be necessary to ensure the reliability of a brain-machine interface, this reliability being based on the complementarity and redundancy of the physiological signs. There is an important field of research to explore for years to come[7].

ANS RECORDINGS AND PHYSICAL PRACTICE

Whether ANS responses could be used to evaluate the peripheral correlates of observation or MI has specifically been questioned in

[6]Hidden Markov Models are used for temporal pattern recognition due to their ability to classify time-sequential data, such as the time-varying physiological signals.

[7]See the publication by Vogt et al. (this special issue), highlighting the growing number of publications on the control of brain-machine interfaces by mental processes such as motor imagery.

the field of sport training and motor rehabilitation. First, the aim was to integrate mental practice to improve motor performance, without any additional physical load.

During the preparation phase of closed skills[8], the participant is likely to mentally rehearse the motor sequence he (she) will perform within the forthcoming seconds. This period is favorable for studying autonomic correlates of MI. In a study involving elite air-rifle shooters, Deschaumes-Molinaro et al. (1992) showed that the concentration phase before shooting elicited autonomic responses very close to those recorded during the forthcoming actual shooting phase. The almost identical nature of ANS responses during the concentration and the actual shooting periods provided evidence that elite shooters recalled memorized routines of shooting by imagining the forthcoming motor sequences through a top-down process, with the aim to better control the forthcoming execution stages. Interestingly, shooting accuracy was better when ANS activity during the concentration period was close to that recorded during actual shooting (Deschaumes-Molinaro et al., 1991). As a consequence, ANS responses were an important factor of final motor performance and could be used to control mental rehearsal during training sessions.

Tremayne and Barry (2001) recorded electrodermal and cardiac activities during the preparation phase of elite pistol shooters. EDA varied as a function of arousal before shooting, attesting the regulation of energy exertion to specific task requirements. Another interesting result is that the pre-shot electrodermal levels were lower for the best performances, as compared with the worst shots. These variations in EDA were paralleled by a pre-shot cardiac deceleration which was longer and more systematic for best than poor shots. As previously mentioned (Porges, 1995b), cardiac deceleration has clearly been linked with attention processes (for review, see Jennings and Van Der Molen, 2005; Bradley, 2009; Thayer et al., 2009). These critical findings underline that reliable information is obtained from the ANS activity, the first being related to variations of arousal, and the second associated with more qualitative processes such as focusing attention (Näätänen, 1973). Skin conductance tonic level is a good index of arousal level and changes in arousal. Skin conductance response (SCR) corresponds to a rapid time-varying response, i.e., phasic activity, usually recorded in response to various stimuli, either from the environment or directly self-triggered by the participant him (her) self who can evoke mentally a movement. The preparation phase is aimed at adjusting tonic level to be aroused adequately, thus enabling to anticipate and process any information needed to perform well. SCR is elicited by each mental evocation of a movement and its duration is highly correlated to the duration of mental representation.

The fact that MI could elicit tonic changes attesting to variations in arousal may be generalized to any motor sequence. This was evidenced in a usual motor activity like walking. Decety et al. (1991) measured cardiac and respiratory activity during actual and mental locomotion as a function of increasing speeds. Wuyam et al. (1995) also studied locomotion on a treadmill to examine whether MI influenced respiration rate. In both experiments, heart rate and respiratory frequency increased proportionately with the mental effort of the imagery experience. Fusi et al. (2005) also confirmed that imagined walking led to a significant, albeit small (less than 10%), increase in ventilation and oxygen consumption, and to larger increases (up to 40%) in respiratory rate, which was paralleled by a non-significant trend toward a decline of tidal volume. Heart rate and respiratory frequency served at evaluating the mental effort attached to the MI of swimming over a distance of 100 m (Beyer et al., 1990). Both heart rate and respiratory frequency increased during the MI session as compared to the control condition, i.e., rest. As previously stated, ANS activity associated with MI is generally weaker than that observed during preparation to actual execution. Decety et al. (1991) provided evidence that the degree of autonomic activation of a subject mentally running at 12 km/h was comparable to that of a subject actually walking at 5 km/h. This gives some validity to the hypothesis we previously stated that the vegetative activity was attenuated in response to imagined movements by comparison to that recorded during the corresponding actual exercise. Overall, based on theoretical background related to CNS organization and on experiments with ANS data recordings, there is now ample evidence of the close link between mental processes and ANS activity. Bolliet et al. (2005a) showed strong and rapid tonic heart rate variations in a group of elite weightlifters when they were requested to imagine lifting a bar. They recorded similar physiological patterns during imagined as during actual movement, although to a lesser extent by comparison with actual lifting, as previously underlined. Heart rate nevertheless increased by about a mean of 30% as early as weightlifters imagined being called by the referee for lifting. Interestingly, changes in skin conductance paralleled those of heart rate. Skin conductance increased during the same preparation period and was also seen as an index of increased arousal. Autonomic correlates in imagined movements were also reported by Wang and Morgan (1992) in the same type of task (imagining lifting dumbbells), albeit with different autonomic indicators, as respiration rate and systolic blood pressure increased by comparison to the control condition. Finally, two studies (Oishi et al., 2000; Oishi and Maeshima, 2004) drew the same conclusion and underlined larger changes in heart rate and respiration. They also provided evidence of the sensitivity of EDA, although this variable is less-used than those from the cardio-respiratory function. Oishi et al. (2000) elected a 500 m speed skating sprint sequence and compared ANS correlates of MI to those associated with another mental effort, e.g., mental arithmetic, and control (rest). They reported a significant decrease of skin resistance associated with increased heart and respiration rates during both MI and mental arithmetic when compared to rest. Skin resistance respectively decreased during MI and mental arithmetic by about 45 and 40%, with no significant difference between both conditions. Heart rate increased significantly above control values in MI (44.3%) and mental arithmetic (10.3%) with, however, smaller increase during mental arithmetic. They finally observed the same response patterns for respiratory rate. Oishi and Maeshima (2004) compared two performance levels (elite and novice speed skaters) and found larger changes in heart rate and respiration in the elite speed skaters group. They

[8]Closed skills occur in a stable environment without uncertainty and confrontation with the opponent is indirectly made. Open skills present reverse features.

also compared motoneurons excitability (soleus H-reflex) during MI and reported decreased motoneurons excitability in the elite skaters group, in contrast to the non-elite athletes. The authors linked autonomic and somatic changes to the effects of central motor programming, as we previously hypothesized. They finally suggested that the descending neural mechanisms reducing motoneurons excitability were activated when vivid MI was internally performed.

THE COPROGRAMMATION OF MOVEMENT BY THE CNS AND THE ANS

As a matter of fact, executive functions might result from programming motor commands at both somatic and autonomic levels of the CNS (Thayer et al., 2009), and is therefore co-programmed, as previously suggested by Mogenson (1977). Consequently, MI can be the first stage of movement since preparing the execution can include mental sequences during which several parts of the movement or even the entire motor sequence may be rehearsed. It was thus postulated that MI enabled conscious access to the infra-conscious operations of motor preparation (Jeannerod, 1994, 1995), and positively impacted motor learning (Jackson et al., 2001). The first effect of MI is to make the ANS mobilizing energy as if the movement would actually be performed. Thill et al. (1997) explained the beneficial effects of MI in terms of central programming structures capable of anticipating the metabolic demands of the task. Hence, distinguishing between movement preparation and mental representation of this movement would be difficult, when considering ANS activity. MI is nevertheless believed at eliciting weaker and shorter ANS activity by comparison to movement preparation for actual execution.

To sum, the activation of autonomic effectors during mental simulation of voluntary movements may originate from motor anticipation of energy consumed by the organism (preparation or anticipation of actual exercise, see Thill et al., 1997) and from the central motor operations of planning/programming occurring before the motor command is sent to peripheral effectors through descending motor pathways (action selection and motor adaptation to the environmental context). Interestingly, we may nevertheless underline that the somatic motor commands are inhibited, at least partially during MI (for a review, see Guillot et al., 2012) while those targeting the autonomic effectors are not, although ANS responses are of lower amplitude and shorter duration than those generally observed during the actual movement. There are thus potential structural and functional dissociations among the efferent systems within this co-programming process (for review, see Collet and Guillot, 2009, 2010).

OUTCOMES THAT COULD BE QUESTIONED

Several contributions have recently questioned these results. Mulder et al. (2005) recorded EMG activity, heart rate and breathing while participants observed or imagined performing squat leg with a 12.5 kg load in each hand. With the exception of respiratory rate, they found no other evidence of ANS correlates in mental processes since variations were comparable to the control condition during both observing and imaging. In particular, heart rate did not significantly change during movement observation. An important issue is that both experimental conditions, i.e., observation and MI did not elicit cardiac changes. Paccalin and Jeannerod (2000) drew the same conclusion since observing a model performing weightlifting movements did not lead to changes in heart rate whereas breathing increased significantly. As stated by the authors themselves, they had no direct explanation for this dissociation between heart rate and respiration. In contrast, several other studies reported an increase in heart rate during the observation (Brown et al., 2013) or the mental representation of effortful action (Papadelis et al., 2007). Self-imaging running on a treadmill at different speeds made the heart rate increasing, although to a lesser extent than changes in the respiratory function (Decety et al., 1991). While Wuyam et al. (1995) did not evidence any significant change in heart rate compared to rest during the mental simulation of running by trained athletes, respiration rate and total ventilation significantly increased. Interestingly, Mulder et al. (2005) deepened their interpretation and suggested possible arguments explaining why heart rate remained unchanged whereas respiratory rate was. They hypothesized that the global analysis of heart rate activity lacked sensitivity to detect more subtle changes related to MI and observation. With a reference to Althaus et al. (1998), they indicated that HRV would probably be more sensitive in detecting slight changes in heart activity. We recently proposed to integrate several ANS correlates of MI in an index designed to evaluate individual abilities to form mental representations of movements (Collet et al., 2011). Among them, we described how respiratory sinus arrhythmia was likely to represent the mental effort required by movement visualization. Although mental effort might objectively cause increased heart rate, changes in the heart associated with MI might better correspond to a change in the pattern of the cardiac signal, by reducing arrhythmia, for example (Grossman et al., 1990). We know that focused attention reduces the differences between higher and lower values of the cardiac signal, i.e., HRV (Porges, 2007b). This is what might happen during MI without changing basal heart rate. Another working hypothesis could also rely on opposite changes in heart rate due to simultaneous requirements of the intensitive and directional functions. In other words, the mental effort during MI could have a stimulatory effect on heart rate due to sympathetic nervous system activation (intensitive function) and, at the same time, a moderating effect on heart rate through the solitary and ambiguous nuclei of the vagal system (directional function controlling focused attention). As previously described by Backs (1998) this could correspond to a co-activation of both the sympathetic and the vagal systems, leading to unchanged heart rate but to reduced sinus arrhythmia.

A remaining question relates on respiratory frequency and this issue was addressed by Paccalin and Jeannerod (2000) and Mulder et al. (2005). While increase in respiratory frequency may be attributable to action observation and MI of the same action, an alternative hypothesis may also be considered. Changes in breathing may be attributable to non-specific factors rather than the content of the visual effortful scene itself. Mulder et al. (2005) supposed a kind of contamination due to the fact that respiration features were directly observable from the model. In other words, the participants could see and hear the respiration rhythm of the observed model and then match their own respiratory frequency with it. This relies to well-known mimic behaviors occurring automatically in the presence of other individuals, for example, the timing of our walking pace with that of the person walking next to us. According to Rizzolatti and Craighero (2004), observing an action made by another person leads to activity in the motor system of the observer which is comparable to that occurring when the observed action is actually performed. Respiration has several features which may be easily observed and perceived through the visual and auditory systems. Observing a model during effortful action may thus lead our own respiration rate to mirror the rhythm of that observed. Thus, the main issue to be addressed is whether changes in respiration features of the observer could be due to a contamination phenomenon or related to the own characteristics of the visual displaying movements. Results by Paccalin and Jeannerod (2000) brought significance to the second hypothesis. First, respiration rate is sensitive to intake and rejection situations. For example, respiration rate decreases during relaxation, when the individual is focused on his(her) own activity (rejection task and top-down process) whereas it is likely to increase in case of processing information from outside (intake task and bottom-up process). The key argument for associating ANS changes to the observed scene is to demonstrate that respiration is influenced by the intensity of the observed effort. Paccalin and Jeannerod (2000) reported that respiration rate was higher when the participants observed an actor walking at high speed by comparison to low speed. Additionally, they found a linear relationship between respiration rate and the running speed of the actor, when the observed sequence was a constant acceleration from 0 to 10 km/h.

More recently, the existence of potential correlations between mental activity and ANS activity was also questioned by Demougeot et al. (2009). The authors claimed that discrete and effortful imagined movements do not specifically activate the ANS. They took cardiac activity and blood pressure as dependent variables potentially influenced by MI of trunk, legs and wrist movements. Acknowledging that MI of cyclical movements is likely to generate intense autonomic activity, their aim was to test whether the same conclusion could be drawn for discrete and intense movements. The authors reported increased cardiac activity and blood pressure during MI of trunk and legs but not during MI of wrist movement. While actual trunk and leg movements resulted in different physiological reactions due to orthostatic hypotension phenomenon, MI of the same motor sequences elicited similar physiological response. More than 89% of the trials made arterial pressure and heart rate increasing during MI, thus suggesting that ANS activation was a consistent phenomenon, observed in most participants. Due to the orthostatic hypotension, heart rate was significantly greater during trunk than leg movements. Conversely, heart rate increased to a similar extent during MI of both trunk and leg movements. Moreover, actual trunk movements decreased arterial pressure due to central blood volume displacement toward the legs, whereas the reverse phenomenon was found for leg movements, i.e., increase in arterial pressure due to the opposite central blood volume displacement. Demougeot et al. (2009) concluded that if such a specific anticipatory mechanism exists during imagined actions, a differential effect of trunk and leg movements on arterial pressure would be expected, but this was not the case. Combining this result with the fact that no physiological activation occurred during MI of horizontal wrist displacements, the authors concluded to non-specific ANS activity during MI. There are however several shortcomings with such interpretation. Firstly, orthostatic hypotension is caused by gravity during postural changes, especially when going from lying down to standing (Ichinose and Nishiyasu, 2012). When the body position varies, several actions occur involving all parts of the cardio-vascular system as well as the ANS that helps to regulate their function. Orthostatic hypotension is compensated by feedback processes, mainly from the baroreceptors. Peripheral vasoconstriction and increased heart rate are the major cardio-vascular adjustments to orthostatic stress and include part of the reflex response elicited via the carotid sinus, the aortic baroreceptors (arterial baroreflex) and cardiopulmonary stretch receptors (cardio-pulmonary baroreflex). Brainstem ANS centers are thus informed about blood pressure and compensate for its decrease by modulating cardiac activity (increase in heart rate and stroke volume) and peripheral vascular resistance (vasoconstriction) through the sympathetic branch. Such compensatory processes adjust blood pressure from feedback which could not be anticipated by central control. Therefore, it seems obvious that similar response from MI sequence could not occur and parallel those observed during actual trunk movement eliciting orthostatic hypotension. Ichinose et al. (2004) and Kamiya et al. (2005) suggested that the upward resetting of arterial baroreflex control in response to orthostatic stress facilitates the activation of sympathetic nerve activity, thereby contributing to the prevention of postural hypotension. Muscle sympathetic nerve activity progressively increases in response to increasing orthostatic stress through the gradual upward resetting of arterial baroreflex control. Although this mechanism is aimed at preventing orthostatic hypotension, this is not an anticipated process. We must acknowledge that in the particular case of ANS modulations of vital parameters (e.g., maintaining blood pressure within values remaining compatible with vital functions) ANS activity during MI becomes decoupled from that occurring during actual movement. This does not mean that ANS correlates of MI are not specific. A second issue which should be addressed from Demougeot et al. (2009) is related to the absence of ANS activity during MI of wrist movement. Movements involving only a part of a body segment are probably less likely to elicit ANS responses than those requiring whole body actions. Cardio-vascular modulations should probably be of very limited amplitude in this case, thus remaining undetectable. The sensitivity limits of the measuring instruments could also be reached and the response associated with MI could be masked by the general cardiac function, especially if the observation time is very short, such as during flexion-extension of the wrist. This time-window was probably too low, especially for identifying changes in blood pressure, whose variations are of higher inertia than those from EDA. Finally, in the absence of specific purpose, we should also question the aim the participants were able to assign to successive wrist flexion and extension, which are not goal-directed movements. Since ANS responses are strongly associated with the emotional significance of the action, we probably have to gain by focusing on goal-directed movement, with the aim to increase the likelihood of recording specific autonomic responses.

AUTONOMIC NERVOUS SYSTEM RESPONSES PATTERN SPECIFICITY DURING OBSERVATION AND MI

As we have just seen, one of the main concerns related to ANS correlates of MI probably relies on response specificity. If we hypothesize that this specificity is real, we should observe different ANS patterns depending on whether the participants are engaged in different imagery modalities, such as internal or external MI perspectives. Ruby and Decety (2001) postulated that differences or similarities between self and other representations may be related to the degrees of self-awareness at the neural level (see also Guillot et al., 2009; Lorey et al., 2009). They reported different patterns of central activation depending on whether each participant self-represented the movement as an actor (internal MI) or a spectator (external MI). Both conditions were associated with common activation in the supplementary motor area, precentral gyrus, precuneus and occipito-temporal junction. The contrast between the third-person (spectator) and the first-person (actor) MI revealed activation in left inferior parietal and somatosensory cortices, thus suggesting that these cerebral areas are specifically involved in distinguishing self-produced actions from those generated by others. This question was early addressed to ANS responses during internal and external MI (Wang and Morgan, 1992).

MOTOR IMAGERY TYPES AND ANS RESPONSES

First, results provided evidence of autonomic changes during MI that were identical to those observed during actual exercise. However, respiratory rate, respiratory exchange ratio, heart rate and diastolic blood pressure were similar during internal and external imagery. The structural distinction observed at the central level was not paralleled by specific patterns of autonomic activity. We cannot conclude at ANS response specificity according to MI modality. Brown et al. (2013) recently stated that observing a motor scene from an internal perspective is more likely to generate ANS activity since the participant feels more engaged than when observing the same motor scene from an external perspective, although the authors did not make this comparison. We should nevertheless underline that the variables used are only derived from cardio-respiratory activity and should be better diversified, especially toward the electrodermal variables. This concern was addressed by Di Rienzo et al. (2012) who studied the effect of physical fatigue on the ability to form accurate mental images, both from the external and the internal MI perspectives. By comparing two dependent variables before and after the participants underwent physical fatigue, they reported no effect on external visual imagery while internal visual imagery accuracy was significantly affected. MI time decreased by about 15% as compared with the “without fatigue” condition whereas electrodermal response decreased by about 48%. Interestingly, these changes only occurred for internal visual imagery, during which each participant imagined the motor sequence as an actor, thus associating the somesthetic cues usually perceived during the actual execution to the representation of the motor sequence. Hence, physical fatigue is likely to specifically affect MI accuracy. This might be explained by updating the internal representation of the motor sequence by taking the actual state of the organism into account before engaging in MI. Feedback from muscle state are believed to alter the ability to perform a motor sequence and provide insights to the reciprocal dependence between mental and motor processes, mediated by ANS activity.

MOTOR IMAGERY AND PERIPHERAL METABOLIC CHANGES

While the general state of the organism may influence the ability to form accurate mental images from the internal perspective, the reverse question could also be asked to test whether mental rehearsal may have the potential to change muscles metabolic parameters. At the level of chemical changes, data do not support the conclusion that MI has changed peripheral metabolic parameters. This issue was early addressed by Decety et al. (1993), who measured muscle metabolism directly using nuclear magnetic resonance spectroscopy during MI sessions. Cardio-respiratory activity was also monitored during both actual and mental leg exercise and increased simultaneously with muscle metabolic changes during actual exercise: drop in phosphocreatine, increase in inorganic phosphate concentrations and fall in intracellular pH to 6.65. End-tidal $P_{(CO2)}$ was unaltered. Under the MI condition, cardio-respiratory activity was comparable to that elicited during actual exercise. Conversely, the metabolic parameters remained unchanged. The end-tidal $P_{(CO2)}$ decreased progressively to about 18% of the resting value during MI due to a greater elimination of CO_2 during hyperventilation without increase in CO_2 production. Under comparable experimental conditions, Wuyam et al. (1995) also reported a reduction in end-tidal $P_{(CO2)}$. This result was later confirmed by Fusi et al. (2005). The monitoring of autonomic changes thus demonstrated that cardio-respiratory activation during MI was greater than that required by the increase in metabolic demands. These results are also in favor of dissociation between somatic and autonomic commands, and provide further evidence for structural and functional similarities between MI and actual motor preparation.

To sum, with the exception of studies by Wang and Morgan (1992), Decety et al. (1993) and Di Rienzo et al. (2012), no other experiment has yet been conducted to address the question of ANS response specificity during MI and new experimental designs, involving a pool of ANS variables including cardio-respiratory as well as EDA, should probably challenge this interesting issue. In the two last paragraphs, we described the potential intra-subject differences through ANS activity. Another way to test ANS responses specificity is to compare central and peripheral response patterns through inter-subjects studies, e.g., when MI is performed by participants with high vs. low imagery abilities.

INTER-INDIVIDUAL DIFFERENCES IN MI IMAGERY ABILITIES

Differences in MI abilities are partially supported by different neural networks (Guillot et al., 2008). The authors compared cerebral activations of skilled imagers to that of unskilled imagers during physical execution and MI. MI abilities were first assessed to assign participants into one of the two groups of skilled and unskilled imagers, using a set of usual tools (questionnaire, mental chronometry and ANS activity recordings). Each group

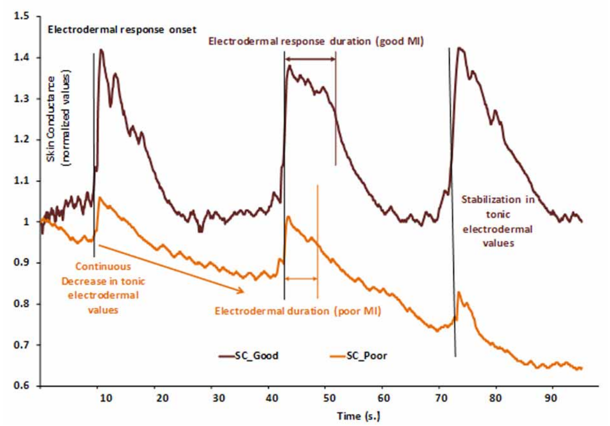

FIGURE 2 | Example of two normalized skin conductance responses during a series of three consecutive MI repetitions of a finger sequence in skilled (SC_Good, dark brown) and unskilled imagers (SC_Poor, light brown). Each vertical bar represents the starting of MI and is paralleled by electrodermal response onset. In the skilled group, electrodermal response duration is comparable to that of the actual finger sequence, thus indicating a close relationship between MI and actual movement durations. Electrodermal tonic values remained at a constant level (around 1), thus attesting that general arousal remained stable and favored general attention. In the unskilled group, electrodermal response is shorter than that of actual movement, thus indicating temporal discrepancy between actual and imagined movement durations. Normalized electrodermal tonic values decreased (from 1.00 to about 0.65), indicating a decrease of general arousal, likely to impair sustained attention. These data suggest that the participant encountered difficulty at keeping arousal at a level that is compatible with efficient cognitive processing. Skin conductance could thus distinguish between MI abilities.

presented a specific pattern of EDA, as illustrated by **Figure 2**. Both groups were then scanned during the mental rehearsal of a sequence of finger movements and activated a set of common cerebral structures including the inferior and superior parietal lobules and motor-related regions such as the lateral and medial premotor cortex, the cerebellum and the putamen. Interestingly, inter-group comparisons showed differences due to MI abilities: good imagers activated more the parietal and the ventrolateral premotor regions, known as playing a critical role in the generation of mental images. By comparison, poor imagers activated more the cerebellum, the orbito-frontal and the posterior cingulate cortices. ANS responses differentiated MI abilities [9] and were paralleled by specific central activation, thus attesting specific inter-subjects differences. Interestingly, this result also gives evidence of a close relationships between MI vividness and electrodermal response duration.

CONCLUSION

Until the two past decades, the ANS was rather considered to control general physiological changes related to variations in arousal, with no actual link with cognitive operations. If this basic function still remains to serve behaviors related to survival, the modern view of its anatomical organization has enlarged its function to more complex social regulation: "The evolution of the ANS provides an organizing principle to interpret the adaptive significance of mammalian affective processes including courting, sexual arousal, and the establishment of enduring social bonds" (Porges, 1998). Each mental operation including MI is thus reflected within a part of our nervous system which is inaccessible to our will and consciousness, but reveals a part of them in the form of specific and structured physiological variations.

Movement observation and MI are both means to interact with our own environment and represent potential operations favoring the mental construction of an action plan. MI is one of the more sophisticated mental operations making the individuals engaging in predictive activities, drawing plans and anticipating the possible consequences of action planning (Jeannerod, 2001). To react appropriately in social relationships, we also have a tendency to simulate how others think of us through MI. These brain operations are accompanied by a set of physiological information which may obviously be recorded at the central level but also at the level of peripheral effectors. Researchers may thus indirectly evaluate mental states and use an inferential model of brain functioning. Variables from the ANS have a good reliability since these are correlated with mental functioning in a specific way. This association is based on a centrally controlled process activating the central representation of movements simultaneously with ANS regulation during MI (Decety et al., 1993; Fusi et al., 2005). Far from the old and outdated views related to ANS functioning, ANS activity provides evidence of a close correlation with cognition (Hugdahl, 1996; Thayer et al., 2009). The sympathetic outflow to the heart is modulated by the activity of the anterior cingulate cortex, and the cardiovagal activity is under the control of the ventral medial prefrontal cortex (Wong et al., 2007). These two cortical structures are known to control both emotional states and cognition. To the same extent, higher control of EDA is mediated by neural networks involving prefrontal, insular, parietal cortices, and limbic structures including cingulate and medial temporal lobe with the amygdala and the hippocampus (Critchley, 2005). The neural substrate for these peripheral autonomic responses is associated with motivational and affective states which, in turn, mediate action observation and MI. Taken as a whole, recording autonomic variables at the peripheral level provides an open window on high brain functions (Collet and Guillot, 2009). These variables can obviously contribute to the study of MI among other neurophysiological and psychological methods (Guillot and Collet, 2005).

While we underlined the common activations of both central and autonomic nervous systems during observation and MI, these are nevertheless associated with no observable behavior. ANS response amplitude and duration are usually reduced when movements are only observed or mentally performed by comparison with actual execution. There are thus potential structural and functional dissociations among the efferent systems within this co-programming process (for review, see Collet and Guillot, 2009, 2010). Dissociated somatic and autonomic co-programming during MI is a working hypothesis waiting for further experimental investigations. As early hypothesized

[9] Sympathetic skin responses were recently used as a quantitative evaluation of motor imagery abilities in individuals with spinal cord injury (Grangeon et al., 2012).

by Damasio et al. (1996), there is high probability that ANS responses accompanying MI may serve as somatic markers constituting a set of information available to the afferent systems as internal feedback. Finally, with reference to biofeedback theories (Schwartz, 1976), learning to self-regulate ANS response patterns may serve subjective experience and enhance the effectiveness of biofeedback procedures by training the individuals to integrate and coordinate central cognitive information to peripheral autonomic and motor responses. Thayer and Lane (2000) presented a theoretical model integrating central and autonomic networks controlling cognitive and affective functions into a structural and functional system designed to serve self-regulation and adaptability of the organism. This system, including the ventromedial prefrontal cortex and the amygdala, is closely linked with autonomic centers in the brainstem and sustains that HRV may serve as a peripheral index of the integrity of CNS networks that support goal directed behavior. A clear relationship is proposed between autonomic activity (e.g., HRV) and executive functions, this being expected to favor a better understanding of the complex interactions between cognitive, affective, behavioral and physiological factors associated with health and disease. As sophisticated mental processes, observation and mental representation could take place within this model. It is a challenge for the future and an open door to new experiments.

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Congruency of gaze metrics in action, imagery and action observation

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The aim of this paper is to provide a review of eye movements during action execution, action observation, and movement imagery. Furthermore, the paper highlights aspects of congruency in gaze metrics between these states. The implications of the imagery, observation, and action gaze congruency are discussed in terms of motor learning and rehabilitation. Future research directions are outlined in order to further the understanding of shared gaze metrics between overt and covert states. Suggestions are made for how researchers and practitioners can structure action observation and movement imagery interventions to maximize (re)learning.

Keywords: action observation, congruency, eye movements, motor learning, movement imagery, neuroscience

Neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), have allowed researchers to locate specific areas of brain activation and highlight the spatial and temporal congruency between observing, executing, and imaging actions. There is now a common understanding that the covert elements (attention, motor planning) of action execution, action observation and movement imagery share, at least in part, similar neural networks and mechanisms (Grézes and Decety, 2001; Holmes et al., 2010). For example, activation of motor cortex and ventral parts of pre-motor cortex has been reported during observation of conspecific actions (Fadiga et al., 1995), as well as movement imagery of an action (Gerardin et al., 2000). Despite significant evidence proposing a partially shared neural pathway, there remains a distinct lack of research identifying the processes by which individuals use information in each of these states and whether there is meaningful congruency between the states. In contrast to imaging techniques such as fMRI, one method of quantifying imagery and observation of goal-directed action is by measuring eye movements, which may provide an online indication of some of the attentional and cognitive processes (Liversedge and Findlay, 2000). This may inform the debate on the meaningfulness of any shared neural substrate. This paper therefore, provides a review of eye movements during action execution, movement imagery and action observation and highlights aspects of congruency in gaze metrics between these states. For a range of gaze metrics we consider clinical and research implications, and translational applications across a number of domains and provide several key research areas that we propose would benefit from further inquiry.

GAZE IN ACTION EXECUTION

An extensive body of research suggests that vision is the dominant sensory system underpinning human function (Causer et al., 2012) and the processes and mechanisms by which vision aids and controls movement have been researched extensively (Elliott et al., 2012). During perception, external visual information is retinoptically mapped (preserved) onto topographically organized areas in the occipital lobe. The "attended" environmental visual cues are then processed via the dorsal, ventral, and rostral streams of the visual system; the dorsal stream permitting identification of object location, size and orientation, the ventral stream facilitating object recognition, and the rostral stream acting as a conduit between both (Goodale and Milner, 1992). In the dorsal stream, which extends into the posterior parietal cortex, the visual and other sensory information is transformed into a common eye-centered frame of reference in motor areas to guide movement (Andersen et al., 1997; Desmurget et al., 1999). Although the degree of correspondence between gaze and stimulus may vary depending upon nature of the task (Frens and Erkelens, 1991; Binsted and Elliott, 1999), the majority of everyday actions such as reaching for a cup or catching a ball are considerably easier and often more accurate with vision. Typically, specific eye movements (visual fixations) precede motor manipulation (Abrams et al., 1990) and during visuomotor tasks such as reach and grasp, the location and duration of these unique eye movements are considered to perform two vital monitoring functions: (1) identifying the goal directed target; and (2) providing visual feedback about the grasping hand to enable online corrections (Land et al., 1999; Brouwer et al., 2009).

Seminal work by Woodworth (1899) suggested that once a stationary target is identified a single ballistic movement occurs that brings the limb into the vicinity of the target. This is then followed by a single corrective movement that is based on visual feedback about the relative positions of the limb and target. Woodworth suggested that the corrective part of the movement involved a graded "homing" in on the target. Over a century later the basic tenets of the two-component theory are still supported by researchers examining the active control of goal-directed movements.

GAZE IN ACTION OBSERVATION

When teaching a movement or skill, demonstrations are frequently used by the instructor (Magill, 2000). These demonstrations are argued to modify behavior through by various mechanisms. For example, an individual may adapt their behaviors to match a model (echokinesis: Prinz, 1987; imitation: Heyes, 2001), an object (emulation: Heyes, 2001) or a perceived goal intention or outcome (Byrne and Russon, 1998). In the skill acquisition/motor learning literature however, observational learning, often referred to as modeling, is seen as more pertinent. Observational learning can be defined as the process by which an individual observes a behavior and adapts his/her action(s) accordingly (Bandura, 1986). The critical difference between observational learning and imitation or emulation is the focus on long-term learning of a skill and a relatively permanent change in behavior rather than a discrete performance. Learning by observation, as well as the ability to recognize and interpret the movements, actions, and goals of others all rely on action observation. Below we will discuss how eye movements are utilized during action observation and the similarities between observing and executing actions.

The direct matching hypothesis (Flanagan and Johansson, 2003) postulates that observing behaviors performed by others elicits motor activity in the brain of the observer similar to that which occurs when the individual plans his/her own actions (Rizzolatti et al., 2001; Rizzolatti and Sinigaglia, 2010). Transcranial magnetic stimulation (TMS) studies have demonstrated that during the observation of goal-directed movements, an increase in a muscle specific motor evoked potential occur in the human motor cortex (Fadiga et al., 1995), and that predictive eye movements are linked to the invoked motor program (Elsner et al., 2013). When observing someone else acting on an object, people implement goal-specific eye movement programs that are driven by their own motor representation for the transient action. Falck-Ytter et al. (2006), for example, demonstrated that proactive goal-directed eye movements in adults result from the direct matching of an observed action with the motor representation of that action. Further, they showed that infants gaze proactively toward the target object of others' actions at the same age as they become able to perform those actions themselves. Elsner et al. (2013) also found that during observation of a conspecific reaching to a target object, stimulation of the observer's motor cortex disrupted the ability to predict the observed actions and was also indexed by delayed predictive eye movements demonstrating eye gaze coupling with motor output.

Action observation is also influenced by observation strategy instructions associated with the stimuli observed. For example, Decety (1996) reported that the neural profile was altered depending on whether the task was to "recognize" the action or to "observe the action with the intent to imitate." Only in the "intent to imitate" condition were areas involved in the planning and generation of movement activated. In addition, the activation was also differentiated by the stimuli presented. Individually-meaningful actions activated the left frontal and temporal (planning) areas whilst meaningless actions activated the right occipital-parietal area. Eye movements have also been shown to be influenced by task strategy. Brouwer et al. (2009) demonstrated a different eye movement pattern dependent upon whether the action involved the viewing of a stationary object or the reach and grasp of that object. During viewing, the eyes fixated the center of mass of the object, whilst during reach and grasp the eyes predictively fixated the future contact areas of the index finger and thumb. These data suggest that when motor plans are generated, gaze performs an active role in action observation, linked to sensory prediction, just as it does in action execution and should be considered in research protocols and intervention designs when providing instructions to participants.

GAZE IN MOVEMENT IMAGERY

Imagery has been shown to influence motor processes, such as the kinematics, kinetics and co-ordination of action, and cognitive process such as motivation, attention and affect (Holmes and Collins, 2001). The use of imagery and, in particular, movement imagery, defined as the representation of human action in the absence of movement execution (Jeannerod and Frak, 1999), has practical implications in a range of domains: music; sport; surgery; military settings; and clinical rehabilitation. Practicing movement imagery, either discretely or, better, in conjunction with physical practice, has been reported to improve motor skill acquisition and performance (Page et al., 2005; Dickstein and Deutsch, 2007).

The concept of eye movement metrics as a useful marker of imagery behavior is not new and the role of gaze and eye movement congruence in imagery has been known for some time. It is surprising, therefore, that researchers and practitioners have not considered the importance of eye movements for image generation. For example, Hebb (1968) suggested that if an image is a reinstatement of the perceptual process then it should include similar eye movements and be constructed in a similar manner. During imagery, the object recognition system (occipital areas and ventral stream) is thought to be primed strongly causing a pattern of neural reactivation (the visual image) to be generated (Kosslyn, 1995). The iterative retrieval of information in the reconstruction of the image is suggested to be assisted by an occulomotor-based coordinate system; eye fixations during perception are encoded, stored alongside the visual representation and used later as an index during systematic image generation (Laeng and Teodorescua, 2002). This suggests that congruent eye movement metrics are an important component in image generation and contribute to two key aspects of the image; its control and quality. This concept is similar to that suggested to operate during visually guided action execution; the action is planned, and updated, in common eye-centered coordinates using information from sensory stimuli and motor effectors (Batista et al., 1999). As with perception, it is possible to scan the visual image and direct attention to key features thus permitting the image's complexity and vividness to be "built up" over time (Kosslyn, 2010). If imagery can be used during skill acquisition and motor (re)learning and eye movements perform a functionally meaningful role, then the efficacy of imagery as a technique for (re)learning may be greater if the eye movements are monitored and controlled during the imagery process.

Despite the extensive research into imagery and imagery mechanisms there remains a paucity of research examining eye movements in movement imagery, where the visual component is clearly important (Jeannerod, 1994). Rodionov et al. (2004) were one of the first groups to examine eye gaze in movement imagery; specifically whether imagination of body rotation could induce oculomotor activity similar to the typical vestibulo-ocular reflex. Their data suggested that nystagmic activity in the horizontal plane could be elicited during movement imagery providing evidence that eye movements could be used as an objective measure of online cognitive processes. More recent research has confirmed the significant role of eye movements in movement imagery with further evidence for functional congruence of eye movements between the covert and overt states (Heremans et al., 2008, 2011; McCormick et al., 2012, 2013). These studies are discussed later in this paper.

CONGRUENCY OF GAZE METRICS

Recording eye movements provides an unobtrusive, sensitive, real-time behavioral index of on-going visual and cognitive processing (Liversedge and Findlay, 2000). This indirect, objective experimental approach has been used successfully to compare behaviors between the observation and imagery by a number of research groups (Flanagan and Johansson, 2003; Heremans et al., 2009; McCormick et al., 2012). Collectively, the findings suggest there are similarities but also some discrete differences between the gaze metrics. The following section provides an overview of this literature and is organized by the states compared.

ACTION EXECUTION AND ACTION OBSERVATION

Flanagan and Johansson (2003) showed that the eye movements of participants observing actors who were performing a block-stacking task were spatially similar to, and in phase with, the eye movements they produced when they performed the task themselves. In both instances, attention was directed proactively to the upcoming point of contact, anticipating the outcome of the actions without attending to the visual unfolding. These anticipatory eye movements in reaching tasks have also been demonstrated in infants as young as 14 months old (Gredebäck et al., 2009). Rotman et al. (2006), in a follow-up study to Flanagan and Johansson, examined eye movements of predictable and unpredictable actions during a similar block-stacking task. Participants observed an actor picking up one of two blocks. The results showed that the observers were able to fixate the goal (target block) through proactive gaze in advance of the actor's hand reaching the goal. These studies suggest that observers are activating their own movement representations for the task being performed by the actor and provide support for the direct matching hypothesis. It should be noted that not all studies have demonstrated proactive eye movements during reach and grasp action observation conditions (see Gesierich et al., 2008), this could be a direct consequence of the instructions provided to participants.

Ambrosini et al. (2011) examined whether these representation transferred into more complex scenarios, where more objects of varying shapes and sizes are present, and whether participants could predict the target object. In a similar set-up, an actor reached for one of two objects, which require two different types of grip. In a control condition the actor did not pre-shape their hand, in the experimental condition the hand was pre-shaped depending on the target object. The results showed that, in the pre-shaping condition, observer's demonstrated earlier saccadic eye movements and higher hand position accuracy compared to the control condition. These data suggest that simply pre-shaping the hand is enough for an observer to identify a target object, providing further support for the idea that when observing others we access the same motor representations as action execution.

Building on these ideas, Ambrosini et al. (2012) asked participants to observe an actor reaching for a target object whilst their hand was either free to move or restrained. Gaze behavior was significantly compromised in the restrained condition with the authors concluding that, when observing actions, it is critical for the observer to be under the same constraints as in action execution. This concept is supported by Costantini et al. (2012), who found that when observing an actor reaching for a target object that was out of reach, proactivity of the observers gaze was compromised.

For relatively simple movements, observers pick up invariant spatial and temporal features from the modeled actions (Mataric and Pomplum, 1998). For instance, in the observation of upper limb movements involving no target, individuals typically fixate the hand or end point, regardless of whether or not the whole limb is used. In situations where the immediate target is unknown, or ambiguous, the observer makes use of other salient motor cues, such as hand pre-shaping, to help identify the appropriate target (Maslovat et al., 2010; Ambrosini et al., 2011). In a similar manner to assisted imagery (Holmes and Collins, 2001), these data suggest information rich visual cues can facilitate observation with the remaining movement details "filled in" using internal models of limb kinematics.

In observation that includes an agent explicitly, the observer's eye movements frequently follow a characteristic sequence. Specifically, the observer typically fixates the agent (generally the agent's head) and then the target (Webb et al., 2010; Letesson and Edwards, 2012; McCormick et al., 2012). It could be that the agent's gaze (and hand trajectory) provides early cues about the anticipated target or goal of the action and/or the sequence is a consequence of specialized neural networks involved in action perception. If action observation uses the same sensorimotor mechanisms as is involved in executing actions, then perhaps observers first attend to the agent to engage these mechanisms or as a necessary pre-requisite of anticipating the target.

A major difficulty in learning through observation is that although individuals are presented with a "model" comprising the task relevant actions, anatomical relationships, kinematic parameters and relative timings, learners may not attend to the important visual information cues. This may occur as a result of divided attention, or because the critical visual cues are not subjectively deemed as "informative" by the observer (Loftus and

Mackworth, 1978), detrimentally affecting subsequent performance (Fernandes and Moscovitch, 2000). In addition, a direct relationship between action execution and action observation implies bi-directionality (Schutz-Bosbach and Prinz, 2007); if perceiving action leads to activation in motor areas then action production (by the self) should also prime action perception. In this regard, if action (by the self) is ineffective (e.g., in movement dysfunction after stroke), then this may influence the patient's perceptual sensitivity to the actions of others. Indeed, Underwood et al. (2009) have demonstrated that domain expertise (enhanced top down knowledge) influences gaze both at recognition and memory recall. Experts in different domains demonstrated more consistent scan patterns when viewing domain specific images, compared to images from an unfamiliar domain. That said, researchers have reported that patients who used action observation as part of their stroke rehabilitation therapy (Ertelt et al., 2007) were able to demonstrate physical improvements compared to controls. These data suggest that during action observation we take advantage of the same motor knowledge that enables us to perform actions. In this regard, the action processing might be modulated by our own motor repertoire as well as the importance we attach to the visuomotor information. In situations where the latter two variables are less than optimal, (re)training effective gaze may improve the level of proficiency achieved through this covert approach to motor (re)learning.

ACTION EXECUTION AND MOVEMENT IMAGERY

Heremans et al. (2008) were the first to compare eye movements between physical execution and subsequent movement imagery. Using a cyclical aiming task the authors reported that 89% of participants made task-related eye movements during imagery with the eyes open and 84% did so during imagery with eyes closed. Furthermore, both the number and amplitude of the eye movements during imagery resembled closely those of eye movements made during the physical execution of the task. The findings contrast, in part, those of McCormick et al. (2013) who reported that additional fixations that were made during physical execution. The differences may be explained through the demands of the actions performed. Heremans et al. (2008) used a relatively low demand cyclic wrist extension action that was cued externally whereas McCormick et al. (2013) employed a task that involved the optimal movement of a stylus to a target in the sagittal plane. These data suggest that the neural coupling that exists between the eye and hand movements during physically executed movements remains partially intact in imagery (i.e., fixation location is preserved). However, the difference in the baseline level of task demand appeared to be uninterpreted in imagery.

In attempts to elucidate the role of eye movements during movement imagery, some researchers have employed chronometry paradigms and included conditions in which eye movements are fixed or free (Gueugneau et al., 2008; Debarnot et al., 2011). Using a joystick tracking task, under normal and mirror conditions, Debarnot et al. (2011) reported that performance accuracy and temporal similarity between physical execution and movement imagery is maintained in the normal condition for eyes-free and eyes-fixed, which suggests that eye movements perform no functional role. However, in the mirror condition the temporal congruence between action execution and movement imagery was maintained only in the eyes-free condition. These data could have occurred as a result of participants in the eyes-fixed condition fixating a cross positioned mid-way between the targets suggesting that peripheral vision may have been used and, given the comparable levels of performance in the normal condition, assisted the task. In more complex tasks, the use of peripheral, rather than high acuity foveal vision may compromise accuracy and results in reduced task proficiency.

In a training study, Heremans et al. (2011) used a Virtual Radial Fitts task where participants were required to have eyes-fixed or allowed spontaneous eye movements. They moved a pen to several targets using their dominant and non-dominant hand. Both groups received movement imagery training; the eyes-fixed group was asked to fixate a red target during the training, whereas the eyes-free group had no eye movement instructions. Results showed that eye movements during movement imagery did not affect the temporal parameters of the action, such as movement time and time to peak velocity, but assisted movement accuracy. These effects were most pronounced in the conditions with high accuracy demands. Effects were found for both the dominant and non-dominant body side, indicating that the effects of movement imagery practice and the role of eye movements during movement imagery practice may be effector-independent.

These studies imply that some of the functional eye movements involved in planning (i.e., determination of the target in the visuomotor workspace) are performed similarly in action execution and movement imagery. It appears that some temporal aspects of gaze (e.g., the functions involved in the online correction of physical movement) are not replicated in imagery.

ACTION OBSERVATION AND MOVEMENT IMAGERY

The concept of a motor representation which is shared by all three simulation states suggests that some gaze metrics should be congruent between action observation and movement imagery, in the absence of any priming action execution. To test this idea, McCormick et al. (2012) used a reach-grasp-place task to examine the gaze congruency between these two conditions and also manipulated visual perspective (first and third person). In the action observation condition participants were instructed to observe the action with the intention to imitate it at a later time. The data showed that although the total number of fixations between conditions (action observation and movement imagery) and perspective was not significantly different, the number of fixations to specific regions of interest (grasp and placement sites) was significantly greater in first, compared to third person perspective. These data suggest that the task related spatial information is influenced by visual perspective; in the absence of a third party agent, information is primarily gathered from the object stimuli. Similar findings have been reported by other research groups (e.g., Letesson and Edwards, 2012). In contrast, McCormick et al. (2012) fixation duration was reported to be significantly longer in action observation than movement imagery. Based on the findings of Loftus and Mackworth (1978), it is suggested that the increased fixation duration reflected the information rich environment of action observation and associated increase in cognitive demand. The number of fixations to target stimuli appears reduced in action observation, and any subsequent movement imagery, when the agent's gaze is visible. Although Humphrey and Underwood (2010) report that the inclusion of social information during picture viewing improves recognition accuracy, it is unknown if social gaze is interpreted in movement imagery and whether it benefits (re)learning in a similar way to action observation.

ACTION EXECUTION, ACTION OBSERVATION, AND MOVEMENT IMAGERY

To date, only one study has compared gaze metrics in all three states within a single paradigm. McCormick et al. (2013) conducted a tri-state comparison of the fixation metrics using a forward reach and point Virtual Radial Fitts' Task. The task required participants to reach and point to three different sized targets on a touchscreen with a stylus. The imagery task was executed in the first person perspective with visual cues (guided imagery) and without cues (unguided imagery). As a manipulation check, simulated movement time during imagery was also recorded. Participants fixated the target in all conditions indicating that similar visual and/or extra-retinal information was acquired in conditions. In contrast to the findings of others (Heremans et al., 2009), more fixations were made to the target during action execution but, in support of McCormick et al. (2012), the number of fixations were comparable between action observation and imagery. The increase in the number of fixations during action execution suggests that corrective fixations occurred during the "homing in" phase of the movement (Elliott et al., 2001). This process of guiding the effector using visual feedback is absent in the covert states. Fixation duration was congruent between action execution and action observation; in both conditions the fixation duration increased as task complexity increased. This increase in fixation may be due to the additional online information processing required in the more complex tasks (Brouwer et al., 2009), due to the eyes remaining fixated at the target until the imminent arrival of the limb (Gowen and Miall, 2006), or a combination of both. In either scenario, the fixation duration in action observation appears to mirror that of action execution and suggests the motor representation, inclusive of eye movements, is shared in these states (Flanagan and Johansson, 2003). The authors also reported that movement time was longer in the imagery conditions compared to action execution and, in contrast to fixation duration, the movement times were constrained by Fitts' Law (Fitts, 1954). As fixation duration remained constant during imagery, and the number of target fixations was comparable with action observation, the authors reasoned that information was attended to differently during imagery and that no online corrective functions were simulated. The inter-state differences and similarities uncovered through these direct tests of the simulation theory highlight that the neural sharedness is partial and differentiated by state. Tri-state comparison therefore, permits identification of the specific gaze characteristics that are congruent between states and guides the further optimization based on a neural sharedness model (Jeannerod, 1994) and this information should be exploited to optimize the effectiveness of observation and imagery interventions.

IMPLICATIONS

We have identified that there are several gaze metrics (e.g., fixation duration and frequency) that have been demonstrated to be congruent between action and simulation states. We have also demonstrated however, that there are several gaze metrics that differ between states. We therefore, encourage practitioners, clinicians, and researchers to consider eye movements and gaze metrics when developing training interventions and therapies, but to be aware that not all gaze metrics are congruent. When designing observation and imagery programs, critical eye movements that are relevant for the given action need to be considered. These important metrics will depend on the task, the context and the individual differences of clients and patients; age, experience, and ability for example.

Practitioners employing imagery and action observation techniques need to be aware not only of the central and peripheral markers, such as cardiovascular responses, but also congruent eye movements as these will provide further evidence that the patients is engaging with the therapy. The transfer of these eye gaze metrics between limbs and similar tasks is also an area of interest and has potential implications for clinical rehabilitation.

TRAINING TOOLS

The research presented highlights the potential of using action observation and movement imagery to (re)learn or improve skills when physical practice is not an option, or in conjunction with physical practice to optimize motor learning. There is an opportunity to use the data presented above to develop a comprehensive action simulation training or therapy program in a clinical environment. Using a multi- and interdisciplinary approach informed by research in neuroscience and psychology as well as the practice of clinicians, the therapy could support motor leaning or regeneration and neural plasticity through a combination of physical practice, action observation and movement imagery (for reviews see Sharma et al., 2006; Holmes and Calmels, 2008; Garrison et al., 2010). The training or therapy, depending on the client group, would need to bring together concepts of motor planning, action prediction, visual attention, and optimal learning to deliver a personalized action simulation package that simulates motor learning in meaningful and contextually-relevant scenarios.

FUTURE DIRECTIONS

The majority of the literature presented in this paper has focused on relatively simple tasks requiring limited visual attention. If the ideas and concepts developed from this work are to be translated into real-world domains for use in skill acquisition and rehabilitation, then these concepts need to be examined in more complex environments under a variety of conditions. For example, future research should manipulate task complexity in order to determine when certain gaze variables, such as fixation duration of saccade amplitude, "break-down" in each of the simulation states. This may provide information to researchers and practitioners looking to train skills using the three different states, for example, fixating a target location for longer and/or earlier (Causer et al., 2011).

Despite the growing research interest in action observation and imagery, most of the studies focus on simple tasks using one limb. Many of the actions we perform in daily life involve the simultaneous action and coordination of at least two limbs. Researchers have shown performance limitations during bimanual movements, evidenced through problems in the planning or execution of the independent movements with both hands concurrently (Punt et al., 2005). Asymmetric movements, with different spatial constraints for the left and right hand can also lead to prolonged latencies, distorted trajectories, and high error rates. These factors are further complicated when one considers the site of infarction and hand dominance in stroke patients. In unimanual reaching, visual attention is deployed to the target well in advance of movement termination. In bimanual reaching, it has been suggested that the independent movement goals (objects) are attended in to in a serial way in the latter part of the task to correct for movement trajectory error (Riek et al., 2003). In contrast, during movement preparation visual attention is suggested to be simultaneously deployed to the independent goals, but with more attention allocated to goals that are perceived as more difficult (Baldauf and Deubel, 2008). How the independent goals are attended to during movement preparation and throughout simulation in action observation and movement imagery is currently unknown. Researchers should investigate how gaze may be affected and controlled during more complex movements and how these translate onto activities of daily living.

In terms of clinical research directions, more research is needed into the use of gaze metrics in rehabilitation and how to optimize skill (re)learning and increasing movement function. In line with this, identification of video feedback and highlighting task relevant cues, via gaze metrics such as fixation zones and fixation duration, especially in high-risk everyday activities, could potentially reduce accidents and injuries, as well as enable patients to relearn skills more effectively following stroke or other movement dysfunctions.

CONCLUSIONS

In this paper we have reviewed critically the literature on eye movements in action execution, action observation, and movement imagery. We identified gaze variables that are congruent and incongruent across states providing an argument for gaze congruency as an implement for developing action observation and movement imagery interventions. We also identified research that supports the idea of a partially shared neural network between the states. We encourage researchers and practitioners to utilize eye movement metrics in experimental and rehabilitation contexts that are representative of the action execution scenario when using action observation and movement imagery interventions. These guidelines can help us move toward more effective training and skill learning in multiple domains, from high performance sports to clinical rehabilitation.

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Watch me if you can: imagery ability moderates observational learning effectiveness

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Recent research has revealed similarities in brain activity during observational learning and motor execution. However, whilst action develops visual, motor and afferent representations during acquisition, action-observation has been proposed to only develop visual-spatial learning via visual representation. In addition, it has been suggested that the vividness of visual representations are determined by imagery ability. Thus, the purpose of the current investigation was to explore the possible moderating role of imagery ability in the effectiveness of observational learning. Participants ($n = 40$) were assessed on their imagery ability via the Vividness of Movement Imagery Questionnaire-2 (VMIQ-2) and then assigned to one of four groups; high imagery ability and observational learning (HIA-OL), low imagery ability and observational learning (LIA-OL), high imagery ability control (HIA-C) and low imagery ability control (LIA-C). Following group allocation all participants performed a pre-test consisting of five actual practice trials of a novel gymnastics routine. The HIA-OL and LIA-OL groups then participated in a 14 day observational learning intervention whilst the HIA-C and LIA-C groups acted as controls. Following this, participants performed a post test, which was identical in nature to the pre-test, before finally completing the VMIQ-2 again. Performance on both the pre-test and post test was evaluated by two qualified gymnastics judges. Results revealed that gymnastics performance increased from pre-test to post test for both the HIA-OL and LIA-OL groups. However, this effect was greater in the HIA-OL group suggesting that the relationship between observational learning and successful imitation performance is moderated by imagery ability.

Keywords: action observation, skill acquisition, motor learning, gymnastics, form tasks

INTRODUCTION

Following recent improvements in the measurement (e.g., PET, fMRI) of cognitive activity in the brain researchers have begun to study the neural correlates between both action observation and movement imitation (Decety et al., 1997; Grezes and Decety, 2001; Filimon et al., 2007). Research in this area has revealed the activation of common neural structures (e.g., Parieto-frontal areas, cerebellum and supplementary motor area (SMA)) between observational learning (OL) and physical practice in both healthy (Macuga and Frey, 2012; Nedelko et al., 2012; Szameitat et al., 2012) and patient populations (Szameitat et al., 2012). Furthermore, recent neuroimaging (Macuga and Frey, 2012) and behavioral research (Ong and Hodges, 2010; Boutin et al., 2012; Ellenbuerger et al., 2012; Hayes et al., 2012a,b) suggests that the activation of these brain regions serve different purposes during OL and actual practice: actual practice results in the development and coding of visual, motor and afferent neural representations of the to-be-learned task, whereas OL leads to the encoding of visual representations (Boutin et al., 2012; Ellenbuerger et al., 2012; Hayes et al., 2012a,b).

The rationale for the development of different neural representations between OL and movement execution derives from proposals that the sensory and motor processes involved in these two paradigms operate differently. That is, learning through movement execution involves the understanding, analyzed and adaption of the interacting effects between the efferent neural commands and afferent neural information (for a review see, Elliott et al., 2010). For example, in order to accurately acquire executed motor skills individuals need to develop internal feed-forward and inverse models. These compare the expected and actual feedback to map the correct movement commands to the required sensory consequences and transform sensory consequences into the correct motor commands, respectively. Whilst actual practice involves all of these motor and sensory transformations, OL affords only some since the observer experiences the same visual input as those in movement execution but does not experience the processes involved either in sending neural commands to the motor periphery or in receiving resultant afferent feedback from movement.

In partial support of the above, Voisin et al. (2011) revealed that OL does not result in actual muscle contraction as measured by EMG. However, EEG data revealed that OL of either a hand action or a hand being passively touched by an object resulted in a modulation of somatosensory activity. Given the lack of EMG activity during OL, the somatosensory modulation most likely resides in processes involved in internal feed-forward models of control. That is, because no actual afferent information is present in OL modulation of activity in somatosensory areas cannot occur due to processes involved in inverse models of control. Rather, the subliminal activation of brain regions during OL may result in efferent copy development and thus development of feed-forward models of control. In support of the possibility that OL enhances feed-forward models, research has revealed that corticospinal activation (measured via motor-evoked potentials; MEP) is greater during OL compared to at rest (Brighina et al., 2000; Aziz-Zadeh et al., 2002; Clark et al., 2004) with the temporal structure of these MEPs sharing the same structure as the muscle phases involved in actual physical practice (Gangitano et al., 2001).

Whilst, OL may well invoke development of the efferent processes involved in motor representations, recent empirical evidence suggest that the sensorimotor processes underpinning OL involve visual rather than complete (i.e., both feed-forward/efferent and inverse/afferent) motor representations (Hayes et al., 2012a,b). Hayes et al. investigated the processes subserving both OL and learning that involves motor execution using both intermanual (Hayes et al., 2012a) and intramanual (Hayes et al., 2012b) transfer paradigms. In the intermanual paradigm, participants learned both the absolute and relative timing of a movement sequence with their right arm either through motor execution or observation before being instructed to perform the same absolute and relative timings with their left arm (i.e., intermanual transfer). Whilst both groups learned the absolute and relative timing of the task equally well when asked to reproduce the same visual-spatial pattern, performance in transfer was significantly lower in the observation group. The intermanual transfer involved the production of a mirror image equivalent to that learned with the right limb. Thus, the authors concluded that the superior performance of the motor execution group was due to this mirrored image engaging homologous muscles to those involved in practice and the motor representations developed therein, whereas, the lower performance of the OL group indicated the development of a visual-spatial (rather than a motor) representation was ineffective in the mirrored task (transfer). To corroborate these suggestions the authors replicated their previous experiment but included an intra- rather than intermanual transfer paradigm (i.e., the transfer task required use of the same limb to that involved in learning, but modification of the scaling between the movement of the limb and the visual-spatial outcome). The rationale being that transfer performance would now be superior in the OL group because the visual-spatial representation formed during practice would be congruent with that required during transfer. Whereas, performance of the motor execution group would be attenuated because the motor representation developed during practice would need to be adjusted to meet the novel motor execution and sensory consequences of the transfer test. Similar to the intermanual experiment, results revealed that both the motor execution and OL groups demonstrated equivalent retention performance. However, participants in the OL group were better able to adapt to the modifications in gain between their limb movements and the associated visual consequences in the transfer test supporting the proposal that learning through action observation results in the development of visual-spatial task representations.

The process of manipulating these types of mental representations (i.e., visuo-spatial images) has been conceptualized in terms of forming, transforming, and maintaining the image (Kosslyn, 1994). These processes not only support the learning and execution of motor performance (e.g., Hardy and Callow, 1999; Fourkas et al., 2006; Guillot et al., 2008, 2009), but also many other important aspects of human functioning. For example, imagery is implicated within working memory (Bywaters et al., 2004), problem solving (Hegarty and Kozhevnikov, 1999) creative thinking (LeBoutillier and Marks, 2003) and language (Bergena et al., 2007). However across these areas, individual differences in imagery ability (e.g., vividness) influence the effectiveness of imagery on functioning (e.g., Gonzalez et al., 1997; Baddeley and Andrade, 2000). Indeed, behavioral research has demonstrated a moderating effect of vividness on motor learning and execution (e.g., Goss et al., 1986; Robin et al., 2007) such that individuals with better imagery ability receive more benefit from imagery use.

Although recent neuroimaging studies have shown differential neural activity and concomitant increased motor output and performance related to ability of imagery (Cui et al., 2007; Guillot et al., 2008; Logie et al., 2011; Williams et al., 2013), a mechanism by which the neural differences underpinning vividness may cause these differential behavioral effects has not been offered. However, a cognitive rationale can be provided. Specifically, a more vivid image provides the imager with clearer information regarding what she or he has to execute via a more detailed visual-spatial representation in working memory (Baddeley and Andrade, 2000), with research indicating that the more detailed the visual-spatial representation, the greater the behavioral response (Callow et al., 2006).

As OL enhances learning and skill development through the development of visual-spatial representations (Hayes et al., 2012a,b) and that ones' ability to produce a vivid image impacts the quality visual representation in working-memory (Baddeley and Andrade, 2000) one might expect that the ability to image (i.e., to create vivid and realistic visual images) might moderate the effectiveness of OL. However, to the best of our knowledge, this proposal has yet to be tested in the literature. Thus the primary purpose of the present study was to investigate whether imagery ability moderates the OL-performance relationship. Further, as OL increases how vivid an image is (Rymal and Ste-Marie, 2009) and also the ease of imaging a movement (Williams et al., 2013), the secondary purpose of the study was to further explore the effect that observational learning has on imagery ability. To examine these aims, participants learned a gymnastic floor routine via an observational learning paradigm and completed a widely used measure of imagery ability Vividness of Movement Imagery Questionnaire-2 (VMIQ-2; Roberts et al., 2008) before and on completion of the intervention. We hypothesized that those participants with higher imagery ability would achieve greater learning, as measured by retention, compared to those participants with lower imagery ability, and that OL would increase imagery ability.

MATERIALS AND METHODS

PARTICIPANTS

Eighty four participants (n = 43 males and 41 females) aged between 18 and 26 (M = 19.8; SD 1.3) volunteered to participate in this experiment. All participants self-reported no previous experience in gymnastics, were naïve to the research hypotheses being tested and gave their consent prior to taking part in the investigation. The experiment was conducted in accordance with the institutions ethical guidelines for research involving human participants. Since the investigation required a high and low imagery ability sample population and due to the experimental task being form based (e.g., a gymnastics routine), participants were screened in regards to their imagery ability and preference. This was achieved via completion of Callow and Roberts (2010) revised VMIQ-2 (see below for specifics). Only those participants with either a high (VMIQ-2 score < 26) or low imagery ability (VMIQ-2 score > 36) and a preference for external visual imagery (EVI) were selected.[1] Following this procedure the investigation was left with 40 participants (12 males, 28 females) aged between 18 and 26 (M = 20.1; SD 1.7) with an equal number of high and low imagery ability participants.

TASK AND APPARATUS

In order to measure imagery ability, participants completed the revised VMIQ-2 (Callow and Roberts, 2010). The revised VMIQ-2 requires athletes to form images of a variety of movements and then rate the vividness of each image. Specifically, the measure contains 12 items and participants are asked to image each item from a specific imagery perspective and rate the image on a 5 point Likert scale according to the degree of clearness and vividness (from 1; perfectly clear to 5; no image at all). The 12 items are then added together to give a score for that imagery subscale. A lower score indicates greater imagery ability. This process is completed separately for External Visual imagery, Internal Visual imagery and Kinesthetic imagery. The questionnaire also requires participants to use a 1–10 (1 = strong internal preference, 5 = no preference, and 10 = strong external preference) Likert scale to rate the extent to which they have a preference for a particular imagery perspective. For the purposes of the current experiment only those individuals who reported 7 or above (≥ moderate external preference) on this question were selected for participation. The VMIQ-2 displays acceptable factorial, concurrent and construct validity (see Roberts et al., 2008).

The experiment took place in a gymnastics hall in which two standard multipurpose gymnastics mats (2m × 1m × 50 mm) were set out horizontally. Marker tape on the mats was used to identify the start position and movements were recorded on a Sony Digital Video Camera Recorder (DCR-DVD106) mounted onto a tripod located at a distance 3.5 meters away from participant and at an angle of 45° (0° was taken as the center of the participants navel). At the start of the experiment, participants were shown a short video ten times[2] on a television monitor (Aiwa VX-G142) of an expert gymnast performing a floor routine. The perspective of the expert in the video was consistent to a third person view or external perspective. Participants were instructed that performance was being measured by how accurately they were able to reproduce the movement form within the video. The routine (see **Figure 1**) consisted of five simplistic movement components each of a comparable level of difficulty, as listed by the *Fédération Internationale de Gymnastique* (2009).[3] Specifically, the movements consisted of a starting position, a lunge, an arabesque, a full turn and a finish position, which were all held for three seconds. For the start position participants were required to balance on their right foot with their left leg bent and their left foot resting on their right knee. Participants had to hold their arms out horizontal in front of their body with their left arm at 45° and their right arm out in front. They had to hold their hands with their palms facing down and their fingers straight. For the lunge participants were required to step forward onto their left foot holding their right leg back straight with their body upright; arms horizontal in front of the body and palms facing down.

[1]The rationale here was that EVI is the most efficacious form of imagery for form based tasks (Hardy and Callow, 1999).

[2]This frequency of demonstration was in accordance with Weeks and Choi (1992) who suggest that this number has been shown to be sufficient for the performer to create an accurate depiction of the skill in their mind (also see, Lawrence et al., 2011).

[3]Fédération Internationale de Gymnastique: The code of points for acrobatic gymnastics 2009–2012. Fédération Internationale de Gymnastique, Suisse. http://www.fig-gymnastics.org

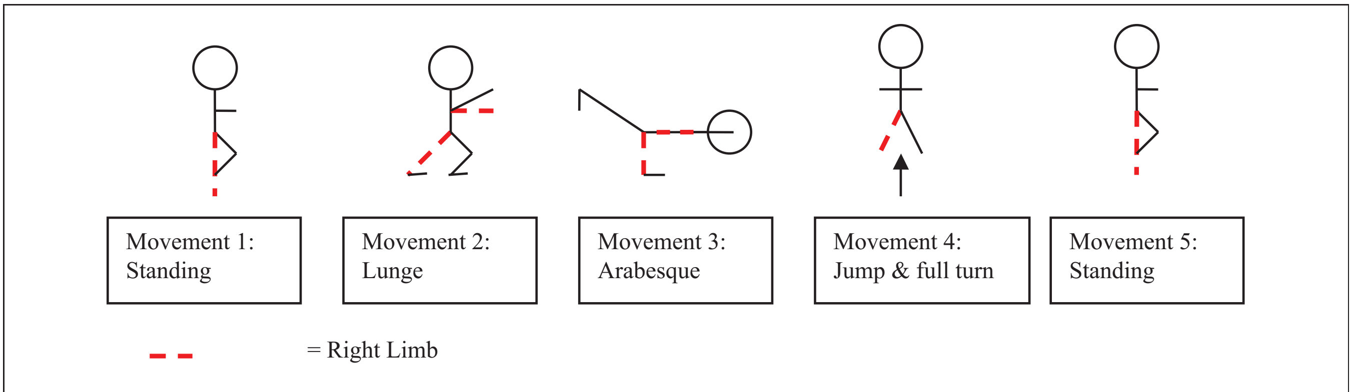

FIGURE 1 | Schematic representation of the five separate gymnastic movements contained within the gymnastics floor routine.

For the arabesque participants were required to stand on their left leg, with their right leg behind, horizontal and straight, and foot pointed. They then had to circle their right arm back until straight behind the body, while holding the left arm horizontal and straight in front of the body, before returning to standing position. For the full turn participants were required to jump in the air swinging their arms forward and overhead for momentum. Participants had to turn their head in the direction of rotation (right), pulling with the opposite shoulder and hips to execute a 360° turn in the air, before landing on two feet, with their arms horizontal in front and palms facing down. The finish position was identical to the starting position.

PROCEDURE

Participants were placed into one of two categories as defined by their score on the VMIQ-2; high imagery ability (VMIQ-2 score < 26; 7 males, 13 females) and low imagery ability (VMIQ-2 score > 36; 5 males, 15 females). Participants within these categories were then randomly assigned to one of two further subcategories. This process resulted in four experimental groups; high imagery ability and observational learning (HIA-OL; 4 males, 6 females), low imagery ability and observational learning (LIA-OL; 3 males, 7 females), high imagery ability control (HIA-C; 3 males, 7 females) and low imagery ability control (LIA-C; 2 males, 8 females). Following group allocation all participants watched the video of the gymnastic routine and immediately performed a pre-test that consisted of one block of five trials of the gymnastics task.

Participants in the HIA-OL and LIA-OL groups then participated in a 14 day observational learning intervention whilst the HIA-C and LIA-C groups acted as controls. Specifically, both the HIA-OL and LIA-OL groups were required to return to the gymnastics hall every day for a period of two weeks in order partake in the observational learning intervention. This consisted of watching the video clip of the expert gymnast 20 times on each visit with a 30 second period between each clip presentation (participants in the HIA-C and LIA-C groups did not receive an intervention). Following this 14 day phase, all participants were given a period of 1 day before performing a post test which was identical in nature to that of the pre-test. Finally, participants were asked to complete the VMIQ-2 for a second time.

DEPENDENT MEASURES AND ANALYSES

All trials were video recorded for analysis. Performance was assessed independently by two experienced gymnastics judges (British Gymnastic Association (BGA) area qualified (Welsh Gymnastics) with 22 years experience and BGA club qualified with 10 years experience, respectively) who were blind to both the research hypotheses and experimental groups, and were not present during testing. Participants were judged according to the *Fédération Internationale de Gymnastique* Code of Points (2009) for Women/Men Artistic Gymnastics (WAG/MAG). Judges were asked to view the video recordings and award points for each trial according to the criteria on the Code of Points, with marks deducted for poor execution and errors. A maximum score of 10 points could be awarded for the whole routine (this was a composite score for all five movements). In order to assess reliability of judging, mean inter-judge reliability scores were calculated and analyzed across all trials. The results of this analysis revealed a significant correlation ($r = 0.901$, $p < .001$), suggesting that participants' performance was rated similarly across both judges for each trial. Following this analysis, the mean of the two independent judges scores were calculated for each trial for each participant. These data were then used to calculate a single mean for the 5 pre-test trials and a single mean for the 5 post-test trials.

To ensure there were no significant differences between the performances of the groups prior to testing, the means of pre-test performance data were submitted to a 4 group (HIA-OL, LIA-OL, HIA-C, LIA-C) one way ANOVA. In order to assess the gymnastics performance data and the imagery ability data VMIQ-2 separate 4 group (HIA-OL, LIA-OL, HIA-C, LIA-C) × 2 experimental phase (pre-test, post-test) ANOVAs with repeated measures on the second factor were conducted. Significant between-subject effects were broken down using Tukeys HSD post hoc tests ($p < .05$) while significant within-subject effects were broken down into their simple main effects ($p < .05$).

RESULTS

PRE-TEST

The one-way ANOVA conducted on the pre-test gymnastics performance data revealed a non significant between group difference, $F_{(3, 36)} = .53$, $p = .67$ (HIA-OL mean = 3.16; HIA-C mean = 2.56; LIA-OL mean = 3.10; LIA-C mean = 2.52). Thus any performance differences at postest cannot be attributed to undue variances between the groups.

GYMNASTICS PERFORMANCE

The analysis of the gymnastics performance data from pre-test to post-test reported significant main effects for experimental phase ($F_{(1, 36)} = 174.66$, $p < .001$, $\eta_p{}^2 = .83$) and group ($F_{(3, 36)} = 4.99$, $p < .01$, $\eta_p{}^2 = .29$), together with a significant experimental phase × group interaction ($F_{(3, 36)} = 56.62$, $p < .001$, $\eta_p{}^2 = .83$). Breakdown of the interaction revealed that only those groups that had experienced the observational learning intervention increased their performance pre to post test (HIA-OL $t(9) = -11.06$, $p < .001$, $i - j = 3.06$, $d = 1.83$, $r = .67$; LIA-OL $t(9) = -6.39$, $p < .001$, $i - j = 1.38$, $d = 0.82$, $r = .38$), with this increase being significantly greater in the high compared to the low imagery ability group (see **Figure 2**). Specifically, whilst performance at pre-test did not significantly differ between groups, performance at post-test was significantly greater in the HIA-OL and LIA-OL groups compared to the control groups, with performance in the HIA-OL group (mean = 6.22, SD ± 1.71) being significantly greater than that of the LIA-OL group (mean = 4.48, SD ± 1.65) ($p < .05$).

In order to corroborate the breakdown of the experimental phase × group interaction, the pre to post test change score was calculated for each group and submitted to a one way ANOVA. Results revealed a significant difference between the means ($F_{(3, 39)} = 56.62$, $p < .001$), with Tukeys HSD indicating significantly greater change scores in the HIA-OL group compared to LIA-OL, HIA-C, and LIA-C groups ($i - j = 1.68$, $p = < .001$, $d = 2.15$, $r = .73$; $i - j = 2.54$, $p = < .001$, $d = 3.94$, $r = .89$: $i - j = 3.18$, $p = < .001$, $d = 5.05$, $r = .93$, respectively). Furthermore, the change scores in the LIA-OL group were significantly greater than those of both the HIA-C $i - j = .86$,

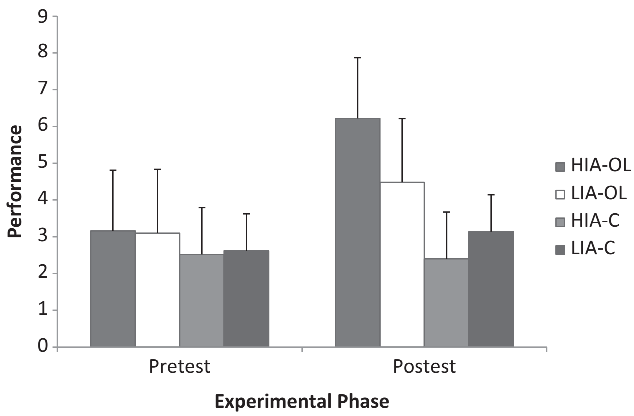

FIGURE 2 | Gymnastics performance as a function of group (HIA-OL = high imagery ability observational learning; LIA-OL = low imagery ability observational learning; HIA-C = high imagery ability control; LIA-C = low imagery ability control) and experimental phase.

$p = .011$, $d = 1.66$, $r = .64$) and LIA-C ($i - j = 1.5$, $p = < .001$, $d = 3.00$, $r = .83$) groups. The control groups were not significantly different to one another ($i - j = 0.64$, $p = .082$).

IMAGERY ABILITY (VMIQ-2)

Analysis of the VMIQ-2 data from pre to post test did reveal a significant main effect of experimental phase ($F_{(1, 36)} = 17.12$, $p < .001$, $\eta_p{}^2 = .32$), and group ($F_{(3, 36)} = 154.13$, $p < .001$, $\eta_p{}^2 = .93$), with scores being significantly lower (indicative of better imagery) post test (pre-test mean = 27.90, post test mean = 25.90) and, not surprisingly, in the high compared to low imagery ability groups. No interaction between the two factors ($F_{(3, 36)} = 2.20$, $p = .11$, $\eta_p{}^2 = .16$) was observed.

DISCUSSION

The present study examined the moderating role of imagery ability on the relationship between OL and performance. Because the effects of OL on motor execution are a function of the visuo-spatial representations developed during learning (Boutin et al., 2012; Ellenbuerger et al., 2012; Hayes et al., 2012a,b) and that the ability to produce vivid and realistic images impacts the quality of visual representation in working-memory (Baddeley and Andrade, 2000), we expected OL to be more beneficial to learning for individuals with high, as opposed to low, imagery ability.

Results revealed that the benefits of OL were significantly greater for participants with higher levels of imagery ability. Specifically, whilst only those groups that had experienced the observational learning intervention increased performance from pre test to post test, this increase was significantly greater in the high compared to the low imagery ability group. These findings indicate that the effectiveness of OL is indeed moderated by the ability to produce a vivid image. Hayes et al. (2012a,b) revealed that the absence of sensorimotor reafference during action-observation enables actions to be represented in visual spatial coordinates only. That is, because participants are at rest during OL they are not directly afforded afferent information from which to develop inverse models (i.e., information involved in the planning and updating of future motor commands). However, despite these OL motor representation limitations, the retention performance (i.e., the exact repetition of the same observed action) following an OL intervention is often similar to that of actual practice (Boutin et al., 2012; Hayes et al., 2012a,b). These results indicate that the direct visuo-spatial replication of the observed movement pattern is possible regardless of whether actual or observed practice interventions have previously been followed. The performance findings of the present investigation suggest that the visuo-spatial replications of the task are more effectively developed in individuals with higher imagery ability. Since visuo-spatial task replications are suggested to be utilized for feed-forward control (Hikosaka et al., 1999) it appears that action-observation developed feed-forward models of motor control are moderated by one's ability to produce vivid images of imagined actions. The same may also be true for the enhanced somatosensory (Voisin et al., 2011) together with corticospinal (Brighina et al., 2000; Aziz-Zadeh et al., 2002; Clark et al., 2004) activity in the absence of actual motor activation during OL. That is, the efferent copy development as a result of subliminal activation of brain regions during OL (Voisin et al., 2011) may be moderated by the imagery ability of the participant. Indeed, if OL is due to somatosensory representation or corticospinal activity alone, then one would not expect to observe greater benefits of OL for individuals with high compared to low imagery ability. As such is it likely that OL involves the development of processes involved in efferent copy and visuo-spatial representation.

Hikosaka et al. (1999) propose that the acquisition of movement patterns involves two distinct, simultaneously developing phases of learning; a fast developing cognitive phase where movements are coded in visual-spatial representations and a slower developing phase where movements are coded in motor representations. Since the OL benefits of the present investigation were moderated by imagery ability, it is possible that the participants with higher imagery ability were able to develop these cognitive visual-spatial representations at a faster rate than their low imagery ability counterparts. In support of this proposal, research has indicated that the SMA, an area that has a dense population of visual coding cells (Georgopoulos, 1991) and plays a critical role in coding a motor response based on visual information (Hayes et al., 2012b), demonstrates greater cortical activation in OL and imagery interventions compared to OL interventions alone (Macuga and Frey, 2012; Nedelko et al., 2012). As such, the increased activation in the SMA associated with imagery may result in more effective and/or faster coding of visual-spatial representations allowing participants with high imagery ability to acquire the cognitive phase of Hikosaka et al. (1999) model at a quicker rate than participants with low imagery ability.

Whilst the current research adopted a 14 day OL intervention, the total duration of the actual observation within this intervention was approximately 140 min (i.e., 20 observations of ∼ a 30 second video per day). Since the present investigation suggests that a possible mechanism for the moderating role of imagery ability on the benefits of this intervention resides in participants developing faster cognitive visual-spatial representations, future research should consider investigating whether longer OL interventions would see a gradual reduction in the moderating role of imagery ability. This is in line with the proposal that the slower developing motor code representation in Hikosaka et al. (1999) model dominants over the visual-spatial representation later in practice. In addition, research has suggested that the amount of practice is thought to be a critical factor to determining when a performer will move from a visuo-spatial to a motor representation for learning (Park and Shea, 2005; Kovacs et al., 2009). Thus, when participants with high imagery ability have completed enough practice to reach a stage where the motor representation phase dominates, it is reasonable to conclude that the benefits of the faster developed (in comparison to those with low imagery ability) visual-spatial representation would be reduced. However, that is not to say that the benefits of OL would be removed following extensive levels of practice, indeed research has revealed the opposite (Stefan et al., 2005; Ray et al., 2013), but rather that the benefits associated with imagery ability would be reduced.

Recently, Williams and Cumming (2012) have also revealed links between OL and imagery. Specifically, the researchers suggest that individuals with high levels of imagery ability demonstrate greater use of both imagery and OL compared to their low imagery ability counterparts. Because the current investigation did not adopt any manipulation checks it is possible that the greater performance at post test of the HIA-OL compared to the LIA-OL group is due in part to participants in the HIA-OL group utilizing imagery during the 14 day OL intervention period. Since it is widely accepted that the use of imagery enhances performance (for a review see, Cumming et al., 2008), this strategy would likely lead to increases in post-test performance. A second potential limitation within the current experimental design is associated with a possible attention effect within the control groups. That is, participants in the HIA-C and LIA-C groups were not required to visit the laboratory during the 14 day OL intervention. Although, all participants were not explicitly aware of the number of groups or the different treatments that the groups received, it is possible that the choice not to include a placebo intervention for the control groups may have resulted in an amotivating effect and a reduction in post-test performance compared to the OL intervention groups.

As well as performance effects, our data demonstrated significant improvements in imagery ability as a result of the OL intervention. While not the primary purpose of the study, these findings do corroborate previous work (see Rymal and Ste-Marie, 2009). Given that imagery ability moderates the effectiveness of imagery on human functioning, as well as OL, ensuring that individuals intending to use these particular cognitive strategies are able to image to a reasonable degree is paramount. Indeed, recent work (e.g., Williams et al., 2013) has demonstrated how imagery training programs can increase imagery ability, and the present investigation provides another useful approach to enhancing this important ability. Due to their apparent simplicity (i.e., watching a demonstration/model) it may be that OL interventions are particularly useful for developing the imagery ability of individuals who have very poor imagery ability or for various clinical populations (e.g., stroke), although this suggestion is somewhat speculative.

To conclude, the present study demonstrates that imagery ability moderates the effectiveness of OL on the acquisition of a motor sequence. The mechanism by which this benefit occurs is likely due to increases in the activation of brain regions (e.g., SMA) associated with the development of visuo-spatial representations deemed particularly important for movement pattern acquisition early in learning (Kosslyn, 1994). This moderating role of imagery ability on OL effectiveness is a novel finding, as such future research should aim to collaborate these effects together with explicitly elucidating the underlying mechanisms involved in order to further advance our understanding of when and how OL is most effective.

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Motor imagery ability in stroke patients: the relationship between implicit and explicit motor imagery measures

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There is little consensus on how motor imagery ability should be measured in stroke patients. In particular it is unclear how two methods tapping different aspects of the motor imagery process relate to each other. The aim of this study was to investigate the relationship between implicit and explicit motor imagery ability by comparing performance of stroke patients and controls on a motor imagery questionnaire and a hand laterality judgment task (HLJT). Sixteen ischemic stroke patients (36 ± 13 weeks post-stroke) and 16 controls, matched by age (51 ± 10 years), gender (7 females) and handedness (3 left-handed), performed a HLJT and completed a motor imagery questionnaire. Our study shows that neither in the healthy controls nor in patients, a correlation is found between the HLJT and the motor imagery questionnaire. Although the patient group scored significantly lower than the control group on the visual motor imagery component ($U = 60$; $p = 0.010$) and the kinesthetic motor imagery component ($U = 63.5$; $p = 0.015$) of the questionnaire, there were no significant differences between patients and controls on accuracy scores of the HLJT. Analyses of the reaction time profiles of patients and controls showed that patient were still able to use an implicit motor imagery strategy in the HLJT task. Our results show that after stroke performance on tests that measure two different aspects of motor imagery ability, e.g., implicit and explicit motor imagery, can be differently affected. These results articulate the complex relation phenomenological experience and the different components of motor imagery have and caution the use of one tool as an instrument for use in screening, selecting and monitoring stroke patients in rehabilitation settings.

Keywords: motor imagery, rehabilitation, hand laterality, phenomenology, questionnaire, implicit, stroke

INTRODUCTION

The ability to imagine or simulate experiences is one of the most extraordinary capabilities of our mind. At first glance, certainly when our brain is intact, we do not realize that this capacity is more complex than the single homogenous capacity of imagery which we experience. Several studies have shown that mental imagery is a multifaceted capacity involving a number of different cognitive functions and brain areas (for a review see Kosslyn et al., 2001). Visual and motor imagery for instance are known to be linked with different neuronal subsystems and there is ample evidence of individual differences in imagery ability (Galton, 1883; Kosslyn, 1980; Richardson, 1994; Borst and Kosslyn, 2010). The present study addresses a specific question relating to measuring motor imagery ability in stroke patients, namely the question of how measures of implicit and explicit motor imagery relate to each other.

The use and explanation of the term motor imagery has led to substantial confusion about what the exact definition of motor, kinesthetic and visual imagery is and how these different perspectives are used by participants in practice. Classically motor imagery was defined as either from an internal, first person, perspective (as if someone was actually performing the imagined movement) or an external, third person, perspective (as if someone watched himself making the movement form outside of his body). Considerable confusion arose whether internal kinesthetic imagery should be dissociated from internal visual imagery (see also Hardy, 1997; Roberts et al., 2008 for a discussion). More recently, several researcher have concluded, independently, that the kinesthetic and first person internal perspective are best measured with a separate subscale in self-report questionnaires, reflecting a consensus on a more differentiated approach to measuring motor imagery ability (Roberts et al., 2008; Williams et al., 2012).

The debate leading to the confusion focused for a large part on the specific modalities in which movements could be imagined. According to Moran et al. (2012) some researchers appear to regard the use of the term kinesthetic motor imagery synonymous with an internal perspective whereas others have shown that the kinesthetic modality could also be experienced concurrently with the use of a third person, external, perspective (Hardy and Callow, 1999; Callow and Hardy, 2004). This latter position is in close accordance with neuroscience research showing that although different networks in the brain are involved with kinesthetic and visual imagery (see Jeannerod, 2001; Kosslyn et al., 2001 for a discussion) that these networks can also be activated simultaneously and are inherently tied to each other (Klatzky, 1994).

Jeannerod, in an influential account on the organization of action control in the brain, argued that representations that are used in the control of motor functions were also used in other cognitive domains, referring to motor imagery as a covert stage of action control (Jeannerod, 1994). Jeannerod and Frak defined motor imagery as "a subliminal activation of the motor system, a system which appears to be involved, not only in producing movements, but also in imagining actions, recognizing tools, learning by observation or even understanding the behavior of other people" (Jeannerod and Frak, 1999). More in particular, Jeannerod made a distinction between implicit and explicit motor imagery. He defined explicit motor imagery as the phenomenological experience where the feeling of the movement was experienced consciously. Explicit motor imagery ability is often measured with an introspective self-report such as the VMIQ-2, the KVIQ and the MIQ-R, where the vividness, clarity or easy with which the imagery is experienced is rated (Malouin et al., 2007; Roberts et al., 2008; Gregg et al., 2010). In contrast with explicit motor imagery, Jeannerod argued that motor imagery is also used implicitly. Here the representations of the motor system are used covertly, without awareness. Task relying on perceptually driven motor decisions, for instance judging whether a depicted hand is a left or a right hand, rely on the covert use of motor images. Also, prospective action judgments, for instance judging whether a dowel is graspable with a particular grip style, are examples of tasks relying on an implicit use of the motor system.

Characteristic of both forms of motor imagery in this account is the fact that the neural structures underpinning motor imagery share a remarkable neurological similarity with neural activity during movement execution. First, several studies showed that during imagination of a movement, more or less the same brain areas are involved as during the actual execution of a movement (Grèzes and Decety, 2001; Jeannerod, 2001; de Lange et al., 2005, 2008). Another similarity between execution and imagery of a movement is the equality in the time needed to mentally and physically perform the same movement (Decety and Jeannerod, 1995), a phenomenon known as mental isochrony. Further, there are strikingly similar physiological changes during movement imagination and actual performance (Guillot and Collet, 2005).

Interestingly, research into both forms of motor imagery, has shown very similar evidence for this covert use of the motor system in motor imagery. For instance, when asked to imagine walking between two points, the duration of the imagined walk is similar to time it would take to actual walk the same distance (Decety et al., 1989), and also shows a similar activity in neural areas used for motor planning and control (Roth et al., 1996). In the same regard, Parsons showed, when perceptually driven motor decisions are made whether a depicted hand is a left or a right hand [the hand laterality judgment task (HLJT)], that the time to judge whether the depicted hand is a left or right hand corresponds to the time it would take to actually perform a rotation of the arm and wrist in the orientation of the depicted hand (Parsons, 1987). Moreover, reaction times also corresponded with the awkwardness of the movement, biomechanical awkward movements took longer to complete, and several researchers showed corresponding activity in the motor areas of the brain when solving the HLJT (Parsons et al., 1995; Vingerhoets et al., 2002). These studies show that the biomechanical constraints and kinematic characteristics of actual movement are reflected in the performance of both implicit and explicit motor imagery measures. Therefore, it appears that implicit and explicit motor imagery are supported by motor representations of the motor system and that these processes seem to rely, at least partly, on equivalent underpinning mechanisms.

There is also long known neuropsychological evidence showing a dissociation between what can be consciously perceived and visual-motor abilities after lesions (see Willingham, 1998 for a discussion). For instance, in the visual-spatial domain, Milner and Goodale (1995) studied a patient who had limited conscious awareness of objects and was unable to recognize everyday objects or identify simple shapes visually. The same patient showed normal visual-motor abilities. The patient was perfectly able to orient a postcard correctly in line with a slit and was able to position the hand and fingers optimally for grasping objects. Examples of patients like the patient described by Milner and Goodale are also part of an on-going discussion about the boundaries between implicit and explicit memory. There is a large body of evidence showing that there are substantial differences between implicit and explicit learning and that these processes rely on different brain systems, although evidence of a partly common mechanism also exist (Dew and Cabeza, 2011). Moreover, it is now evident that motor skills can be learned implicitly (Masters, 1992; Jiménez and Méndez, 1999, 2001; Maxwell et al., 2003), even after stroke (Pohl et al., 2001; Orrell et al., 2006) without being consciously aware of what is learned. Moreover, in the domain of visual imagery an interesting study of a patient is described by Zeman et al. (2010) who rated himself as having almost no subjective visual imagery experiences.

These findings are relevant for recent developments in the field of rehabilitation. In the past decades motor imagery is increasingly been recommended as an additional technique that can be used for motor recovery in stroke rehabilitation (Jackson et al., 2001; Sharma et al., 2006; de Vries and Mulder, 2007). Herein, there has recently been an advocacy for the use of instruments to assess motor imagery ability of patients before they enter rehabilitation programs where motor imagery is used (Jackson et al., 2001; Braun et al., 2006, 2013 in this issue; de Vries and Mulder, 2007; Simmons et al., 2008) And, although a recent review has shown that a large number of studies still do not use motor imagery ability measures (Malouin et al., 2013 in this issue) a number of them do and they include both implicit and as well as explicit measures and there are also advances in developing instruments specific for the use in rehabilitation settings (Malouin et al., 2007, 2009; Gregg et al., 2010; Butler et al., 2012). However, there has been surprisingly little research about how self-report questionnaires that assess the vividness or ease of motor imagery ability relate to measures of implicit motor imagery when administered to stroke patients. To date, there is no consensus which instruments should be part of a motor imagery ability assessment and researchers use different instruments for screening purposes. In some studies implicit measures are used, others use only self-report questionnaires whereas others use a mix of different methods for assessing motor imagery ability. Given that lesions to the action system can affect implicit and explicit cognitive processing differently (see Willingham, 1998; Dew and Cabeza, 2011 for a discussion) shows that it is important to establish what the relationship between measures for implicit motor imagery ability and self-report rating is, particularly in the stroke population.

A recent study by McAvinue and Robertson (2007) with young healthy adults using a large test battery of motor and visual imagery measures is one of the few studies which shed some light on this issue. They showed that self-report ratings of motor imagery ability and tests that measure implicit motor imagery ability loaded onto different components, suggesting (in accordance with Jeannerod) an implicit and explicit component for motor imagery. In the same regard, Collet et al. (2011) have noticed that individual performance on different measures for motor imagery could vary and have made the suggestion that motor imagery ability might be best measured by using a combination score of different measures. However, these were studies including healthy adults which makes it difficult to generalize these findings to the stroke population. A study on stroke patients by Schwoebel and Coslett (2005) did also show evidence for a double dissociation between measures that require implicit judgments and measures that require explicit judgments. However, Schwoebel and Coslett did not include self-report ratings of the subjective experience of motor imagery in their study.

Given the lack of studies in stroke patients on the relationship between explicit self—report ratings and implicit measures of motor imagery ability it is unclear how they relate to each other. It could be that when a patient is impaired on one measure that he is also likely impaired on the other. However, the research by McAvinue and Robertson (2007) and Schwoebel and Coslett (2005) suggest that this need not be the case. Also, the study of the patient described Zeman et al. (2010) showed that, in the domain of visual imagery, the subjective experience of visual imagery could be absent after brain injury. A better insight in how implicit and subjective experience of explicit motor imagery relate to each other could contribute to a consensus on how motor imagery ability instruments can be used in the rehabilitation practice. Therefore, the aim of this study was to explore the prevalence of implicit and explicit motor imagery ability impairments and investigate the relationship between implicit and explicit motor imagery ability by comparing performance of stroke patients and controls on two different methods tapping both aspects of motor imagery.

Phenomenological self-report ratings that measure the vividness or ease of motor imagery ability require a conscious explicit judgment. Therefore, we used a motor imagery questionnaire, the MIQ-RS (Gregg et al., 2010), for measuring explicit motor imagery ability. A second method, perceptually driven motor decision tasks requires an unconscious judgment from the participant. Therefore, the HLJT was used for measuring implicit motor imagery ability (Parsons, 1987). We used the MIQ-RS because of the focus in this scale on items related to hand functioning. Thereby maximizing it's similarity with the HLJT. A simple choice reaction time task and a visual mental rotation task were used to control for non-motor-imagery specific cognitive impairments. With this setup we wanted to study what the prevalence of impairments on these instruments was and study the relationship between these measures of motor imagery ability is in stroke patients. Based on the results of the neuropsychological studies showing a dissociation between implicit and explicit cognitive processes and the study of McAvinue and Robertson (2007) where in healthy adults no correlation between the measures for implicit and explicit motor imagery were found we expected that patients would perform more poorly than controls on motor imagery tests but that conscious awareness of the ease with which a movement is imagined does not have to correlate with implicit motor imagery ability.

MATERIALS AND METHODS

PARTICIPANTS

In total sixteen patients (7 female, mean age 51.06 ± 10.74 years, 3 left-handed, 7 right hemisphere lesions) recovering from an ischemic stroke (36 ± 13 weeks ago) participated on voluntary basis in this the study. The participants took part in this study as part of a longitudinal study on monitoring motor imagery ability in stroke patients. Patients were recruited from stroke units of two rehabilitation centers in the Netherlands, UMCG Beatrixoord in Haren and Rehabilitation Friesland in Beetsterzwaag. A control group of sixteen healthy participants, matched by gender, age (51.38 ± 10.03 years) and handedness (Oldfield, 1971), were included. The ethical committee of the medical center of the University of Groningen approved the study protocol and a written informed consent was obtained from each participant before entering this study. The major inclusion criteria were a unilateral impaired motor function of the upper limb following stroke [wrist dorsiflexion, MRC < 5 (Gregson et al., 2000)] and stroke onset 16–52 weeks prior to participation in this study. Patients were excluded when they had a history of repeated strokes, severe cognitive dysfunction [MMSE < 24 (Folstein et al., 1975)], severe receptive aphasia (inability to understand test instructions), neglect, visual problems, neurological disorders or comorbidity which could interfere with this study. Patients had to be able to understand Dutch. Further, patients that participated in another intensive study were not able to participate in this study.

INSTRUMENTS

Explicit motor imagery: motor imagery questionnaire

A motor imagery questionnaire based on the MIQ-RS was administrated as an explicit motor imagery task (Gregg et al., 2010). The MIQ-RS was chosen because it includes items of functional tasks specifically aimed at hand movements (e.g., grasp a glass, push a door). Thereby, the items of the MIQ-RS correspond closely to the HLJT. The MIQ-RS questionnaire is shown to be a reliable and valid measure for motor imagery ability (Gregg et al., 2010) and is developed specifically as an instrument for the stroke population (Butler et al., 2012). Although the MIQ-RS is specifically aimed at this population, some adjustments in the protocol had to be made for administration in patients with more severe motor impairments. First, not all participants managed to completely perform the movement physically because of the variability in motor function of the upper extremity and difficulties of some patient to stand unsupported. Therefore, the test leader demonstrated the movements that had to be imagined to the participants. All participants performed the test in a sitting position. Patients as well as controls performed this task procedure in the same manner. To facilitate imagery from an internal first person perspective the examiner took place next to the participant while demonstrating the movement and participants were instructed to imagine from a first person perspective. Second, in the original MIQ-RS each action was administrated two times (from a first person visual and a kinesthetic perspective), but in our study also the non-dominant and dominant sides were assessed separately, as is suggested by Malouin et al. (2007). Adherence to the goals of the items in the questionnaire was checked by the examiner by asking how the participant imagined the action by asking what the person saw and felt.

Each item consists of the following stepwise procedure. First, the participant was asked to assume the start position: sitting on a chair with backrest and with their hands on their lap. Second, the examiner sat on a chair in front of the participant and then took place next to the participant and demonstrated a movement supported by a verbal description of that movement. Third, the experimenter took place in front of the participant and participants were asked to close their eyes and imagine either seeing or feeling as clear and vivid as possible the just demonstrated movement. In the last step of each item, the participant had to rate their experience of the ease/difficulty they could imagine the movement on an ordinal rating scale from 1 (very hard to feel/see) up to 7 (very easy to feel/see) from the visual and the kinesthetic perspective (For a detail description of the used items, instructions and protocol see Gregg et al., 2010).

Implicit motor imagery: computerized imagery task

We used a computerized task that consisted of three parts; a simple choice reaction time task, a visual imagery task and a HLJT. During the computer test, all participants sat in front of a laptop screen in a chair with a backrest. All participants started with the simple choice reaction time task. The visual imagery task and the HLJT were randomized between participants. In all three tasks, two types of stimuli were presented on the computer screen. The participants had to react as fast and accurate as possible on these stimuli by pressing the left or right button on a response box (Psychological Software Tools, Pittsburgh, PA). The stimulus disappeared from the screen when the participant pressed the button or when the stimulus was presented for 10 s. The responses were given with the hand of the unaffected limb. Their matched controls executed the task with the same hand regardless of their hand dominance to control for confounding effects. For each task performance was assessed by calculating the average response time (in milliseconds) and the accuracy (percentage of correct responses). Before the start of each test, the participant had the opportunity to practice the task in a block of 48 stimuli. The visual imagery task and the HLJT each contained a total 216 stimuli, divided in three blocks of 72 stimuli with a short break period between the blocks.

Simple choice reaction time task. A simple choice reaction time task was included to control whether simple reaction time was affected in stroke patients. The HLJT is based on time isochrony and therefore it is important to control whether a latency in reaction time on the HLJT is the result of impaired motor imagery ability instead of a more general impaired reaction time. The participants had to react to two types of presented stimuli, an "O" or "X," by pressing respectively the left or right button on a response box.

Hand laterality judgment task. Implicit motor imagery was assessed with a HLJT (Parsons, 1987). Participants had to determine the laterality of a rotated hand presented on the computer screen. The hands were shown from the backside or palm side of the hand. The stimuli of presented hands were rotated at six different angles, covering the full circle at a spacing of 60° (0, 60, 120, 180, 240, 300°). The orientation of the hand with fingers pointing upward was defined as an angle of 0°. Participants had to react to these stimuli by pressing the button (left or right) corresponding to the laterality of the hand. The participants were not allowed to rotate their hand or look at their own hand during this task. Adherence to this task procedure was carefully controlled by the experiment leader, who was present during the whole experiment.

Visual imagery task. The visual imagery task (de Lange et al., 2005) was included in this study to control whether the participants performance on the HLJT was related to visual imagery ability. Stimuli of mirror-reversed and regular capital alphabetic characters, "R" and "F," were presented on the computer screen. The characters were rotated at the same angles (0, 60, 120, 180, 240, 300°) as stimuli in HLJT. The orientation when the "R" or "F" was upright was described as an angle of 0°. Participants had to decide as fast and accurate as possible whether the letter was a mirror-reversed or a normal letter by pressing respectively the left or right button on the response box.

Brunnström Fugl-Meyer scale

The arm-hand function of the affected limb was administrated with the Brunnström Fugl-Meyer scale (BFM) (Fuglmeyer et al., 1975). The Fugl-Meyer scale is shown to be a reliable and valid tool for the evaluation of motor recovery in stroke patients (Gladstone et al., 2002). This test is used in clinical settings for determining reflexes, movement, coordination and speed of the upper extremity. Each item could be scored with 0–2 points on an ordinal scale (0 = no movement possible; 1 = impaired movements possible; 2 = movements possible). A total score was inside a range of 0–60 points, because reflexes were not examined in this study.

Utrecht arm/hand Test

The Utrecht Arm/hand Test (UAT) is a clinical measure to obtain the arm-hand function of patients (van Reenen et al., 2001). The items of this test are scored on an ordinal scale where eight items represent the following function of the upper limb: a-functional arm (score 0); flexion-synergy (score 1), first distal selectivity (score 2), wrist dorsal flexion (score 3), hook grip (score 4), cylinder grasp (score 5), tweezers grasp (score 6), and clumsy hand (score 7).

PROCEDURE

The testing procedure was similar for all participants. The assessment took place in a quiet room in one of the rehabilitation centers or at home. The measurement started with the computerized imagery tasks. This was followed by the examination of the motor function. Finally, the MIQ-RS questionnaire was completed by the participants.

DATA ANALYSIS

For the computer task, mean reaction times of correct responses and mean accuracy scores of responses with a latency between 350 and 10.00 ms were calculated and included in the analysis. First analyses revealed no differences between stimuli or items of the affected or the non-affected limb in patients and therefore left and right stimuli were grouped together for both the questionnaire as well as for the computer task. First a reliability analysis was done for the visual and kinesthetic component of the adapted MIQ-RS. Then total mean scores were calculated for the visual and kinesthetic components of the adapted MIQ-RS. In accordance with Page et al. (2001), who used a cut-off of 25 (on a maximum of 56 on the original MIQ-R scale), a mean score on one of the subscales below section Differences in Imagery Ability Between Patients and Controls was considered as low imagery ability. Because of non-normal distributed data, non-parametric tests were used for analysis. The difference between the control and the patient group was determined with a Mann-Whitney U test, with $\alpha < 0.05$. To control whether individual patients differed significantly on the computer task from the control group, a modified T-test with $\alpha < 0.05$ was used (Crawford and Howell, 1998). The relationship between the MIQ-RS, HLJT, visual imagery task, BFM, and UAT was calculated with a Spearman correlation coefficient. Finally, to determine which strategies were used by the patients and the control group, separate repeated measures ANOVAs were performed on the RTs for the HLJT and the visual imagery task. To determine whether participants still use a motor strategy in solving a motor imagery task the stimuli were collapsed in sets of comfortable (medial) and awkward (lateral) orientations resulting in two within-participants factors for the ANOVA: biomechanical orientation (awkward, comfortable) and rotation (60, 120°), and with group (patients, controls) as a between-subjects factor. A corresponding ANOVA setup was also used for the visual imagery task with alphanumeric character orientation (clockwise, anticlockwise) and rotation (60, 120°) as within-subject factors, and with group (patients, controls) as a between-subjects factor. All data were analyzed with IBM SPSS version 17.0.

RESULTS

INTERNAL RELIABILITY

Cronbach's alpha for the visual motor imagery subscale of the MIQ-RS was high with $\alpha = 0.98$ for the patient group, and $\alpha = 0.95$ for the control group. Cronbach's alpha for the kinesthetic motor imagery subscale of the MIQ-RS was also high with $\alpha = 0.98$ for the patient group, and $\alpha = 0.98$ for the control group.

DIFFERENCES IN IMAGERY ABILITY BETWEEN PATIENTS AND CONTROLS

Patient group vs. control group

Table 1 shows the results on the questionnaire and HLJT for the group of patients and the group of controls. Patients scored significantly lower on both, the visual motor imagery component ($U = 60$; $p = 0.010$) and the kinesthetic motor imagery component ($U = 63.5$; $p = 0.015$) of the MIQ-RS compared to controls. In the simple choice reaction time task, the reaction time did not differ significantly between the group of patients and controls ($U = 24$; $p = 0.200$). Also the accuracy on this task was similar for both groups ($U = 105.5$; $p = 0.355$). The patients reacted slower on the visual imagery task ($U = 68$; $p = 0.024$) as well as on HLJT ($U = 58$; $p = 0.008$) compared to the control group. No significant differences between patients and controls were found on the visual imagery accuracy score ($U = 93.5$; $p = 0.189$) and the accuracy score on the HLJT ($U = 111.5$; $p = 0.532$).

Individual patients vs. control group

The individual score of patients on the questionnaire, hand laterality task and the BFM and UAT are shown in **Table 1**. Six out of the 16 patients (37.5%) scored below the cut-off on the visual imagery component of the questionnaire indicating impaired visual motor imagery ability. Eight patients (50%) scored below the cut-off on the kinesthetic imagery component of the questionnaire indicating impaired kinesthetic imagery ability. Three patients scored lower on the kinesthetic component without scoring lower on the visual component of the MIQ-RS (patients 5, 13, and 16). One patient, patient 14 scored lower on the visual component of the motor imagery scale without scoring lower on the kinesthetic component. A significantly lower reaction time than the control group was found for two patients in the simple choice reaction time task, two patients in the visual motor imagery task, and three patients in the HLJT. Patient 2 (see **Table 1**) scored significantly below the mean reaction time of the control group on all three tasks. Two of the 16 patients had significantly lower accuracy scores both on the visual imagery task and HLJT. Two patients showed less accurate responses independently on the visual imagery task and one patient only on the HLJT. Only one of the patients with low accuracy scores on one of the computerized imagery tasks scored at around chance level (patient 5). All other patients scored well above chance on the computerized imagery tasks.

CORRELATION BETWEEN THE QUESTIONNAIRE, THE HAND LATERALITY TASK AND THE VISUAL IMAGERY TASK

The Spearman correlation coefficients between MIQ-RS and the computerized imagery task for the groups of controls and patients are respectively shown in **Tables 2**, **3**. No significant correlation was found between the scores on the components of questionnaire and hand laterality task or visual imagery task for patients or controls. A significant positive correlation between the visual and kinesthetic motor imagery component of the questionnaire was found in both groups. This was the only significant correlation between imagery measures in patients. There were no significant correlations between measures for implicit and explicit motor imagery in both groups. **Table 2** shows, for the control group, a

Table 1 | Scores (mean/*SD*) on the MIQ-RS and hand laterality task, the object identification task and the visual imagery task for the group of controls and patients and the individual patient scores for the UAT and BFM (*N* = 16).

	MIQ-RS		SCT		VIT		HLJT		UAT	BFM
	V	K	RT	ACC	RT	ACC	RT	ACC		
Controls	5.9 (1.0)	4.9 (2.0)	479 ± 86	98 ± 3	903 ± 249	97 ± 3	1704 ± 564	93 ± 5		
Patients	4.0 (2.1)*	3.1(2.1)*	523 ± 95	98 ± 2	1118 ± 227*	94 ± 7	2568 ± 902*	89 ± 1		
1	7.0	7.0	470	96	1275	100	4873*	94	7	60
2	1.1+	1.0+	698*	100	1574*	93	3322*	93	3	31
3	2.9+	1.6+	579	96	830	99	2368	87	6	59
4	1.0+	1.0+	378	98	981	96	1560	96	7	59
5	4.9	1.7+	554	100	1493*	93	1827	39*	7	60
6	4.8	5.1	494	96	1301	96	2525	93	7	55
7	4.4	4.0	685*	98	1034	89*	1866	91	7	58
8	6.3	5.2	496	96	968	77*	2462	78*	7	60
9	5.4	5.4	540	96	1120	83*	3414*	81*	6	35
10	1.9+	1.0+	563	98	1194	88*	1632	99	0	0
11	6.2	5.8	445	98	799	99	1505	98	7	58
12	3.6	3.6	421	100	863	100	2565	94	0	2
13	6.0	1.0+	658	100	1074	98	2560	98	4	34
14	1.6+	3.4	470	100	964	100	2311	94	6	55
15	1.1+	1.2+	421	98	1303	97	3755*	97	7	59
16	6	2.0+	500	100	1112	94	2536	92	7	60

SCT, Simple choice task; VIT, Visual Imagery Task; HLJT, Hand Laterality Judgment Task; V, visual motor imagery component (score); K, kinesthetic imagery component (score); RT, reaction time (ms); ACC, accuracy (% correct responses).

**Significantly different compared to the control group.*

+Below the cut-off score.

high significant positive correlation between the accuracy of the HLJT and visual imagery task. The positive correlation between the reaction time of implicit HLJT and the visual imagery task was also significant in the control group. The reaction time on the visual imagery task was negatively correlated with the accuracy on the same task in the control group. No significant correlation was found between the UAT and BFM and the different types of imagery. The UAT and BFM did correlate significantly with each other.

REACTION TIME ANALYSIS

A repeated measures ANOVA on the reaction time scores of the HLJT showed a main effect of orientation, with $F_{(1,\ 30)} = 13,\ 78$, $p < 0.01$, rotation, with $F_{(1,\ 30)} = 40,\ 24$, $p < 0.001$ and a significant interaction between orientation and group, with $F_{(1,\ 30)} = 5,\ 58$, $p < 0.05$, rotation and group, with $F_{(1,\ 30)} = 7,\ 62$, $p < 0.05$ and between orientation and rotation, with $F_{(1,\ 30)} = 4,\ 20$, $p = 0.05$. *Post-hoc* analysis showed that patients were significantly slower than controls on lateral, more awkward, orientated stimuli of hands than on medial orientations with the same extend of rotation. Analysis of the reaction times of the visual imagery task only showed a main effect of rotation with $F_{(1,\ 30)} = 96,\ 13$, $p < 0.001$. No further main or interaction effects were found for the visual imagery task.

DISCUSSION

With this study we wanted to explore the prevalence of implicit and explicit motor imagery ability impairments and investigate the relationship between implicit and explicit motor imagery ability measures in stroke patients. Patients in this study scored significantly below controls on both the visual and the kinesthetic component of the adapted MIQ-RS. However, they did not differ significantly from the control group on the accuracy scores of the HLJT or the visual imagery task. More importantly, our results showed that there is discrepancy between performance of stroke patients on the explicit and implicit motor imagery tasks. The results from this study showed no significant correlations between the HLJT and the MIQ-RS. Neither in stroke patients, nor in age matched controls, a significant correlation between implicit and self-reported explicit motor imagery ability was found. To our knowledge this the first time that a divergence between results on a phenomenological explicit motor imagery measure and an implicit motor imagery measure is shown in stroke patients.

Our results show that the subjective experience of the ease of imagining a movement does not have to be related to implicit motor imagery ability after stroke. These results are in line with the model of overt and covert action simulation and the distinction therein between explicit and implicit motor imagery proposed by Jeannerod (2001). The results are also in close accordance with the study of McAvinue and Robertson (2007) where also no correlation between implicit and explicit motor imagery was found. However, in the study of McAvinue and Robertson (2007) only healthy adults were included. In our study we extend these results by showing that also in stroke patients no correlation is found between the phenomenological experience of motor imagery and the performance on implicit motor imagery ability.

Table 2 | Spearman correlations between the questionnaire, hand laterality task visual imagery task of controls ($N = 16$).

		Questionnaire		Hand laterality task		Visual imagery task	
		V	**K**	**RT**	**ACC**	**RT**	**ACC**
Questionnaire	V	1					
	K	0.50*	1				
Hand laterality task	RT	0.00	−0.13	1			
	ACC	0.35	0.26	−0.27	1		
Visual imagery task	RT	−0.15	−0.06	0.86**	−0.48	1	
	ACC	0.32	0.20	−0.37	0.67**	−0.53*	1

V, visual motor imagery component (score); K, kinesthetic imagery component (score); RT, reaction time; ACC, accuracy.
$^{*}p < 0.05$ $^{**}p < 0.01$.

Table 3 | Spearman correlations between the questionnaire, the hand laterality task and the visual imagery task of patients ($N = 16$).

		Questionnaire		Hand laterality task		Visual imagery task		Motor function	
		V	**K**	**RT**	**ACC**	**RT**	**ACC**	**BFM**	**UAT**
Questionnaire	V	1							
	K	0.69**	1						
Hand laterality task	RT	0.14	0.15	1					
	ACC	−0.23	−0.32	−0.10	1				
Visual imagery task	RT	−0.13	−0.25	0.42	−0.11	1			
	ACC	−0.04	0.10	0.14	0.43	−0.37	1		
Motor function	BFM	0.38	0.30	−0.04	−0.45	0.02	−0.02	1	
	UAT	0.33	0.42	−0.16	−0.27	0.08	−0.09	0.83**	1

V, visual motor imagery component (score); K, kinesthetic imagery component (score); RT, reaction time (ms); ACC, accuracy % correct responses).
$^{**}p < 0.01$.

In the light of the recent advocacy for screening for motor imagery ability in motor-imagery based rehabilitation programs (Jackson et al., 2001; Braun et al., 2006, 2013 in this issue; de Vries and Mulder, 2007; Simmons et al., 2008) these results have an important clinical implication. Our study shows that by selecting patients on the basis of subjective reports only, researchers could risk excluding patients that might still have intact motor imagery ability. Therefore, a screening procedure where different imagery measures are used seems more appropriate for the use of screening stroke patients in motor-imagery based rehabilitation programs.

We used the MIQ-RS as a measure for the vividness of explicit motor imagery ability. We chose the MIQ-RS specifically because of the items in this questionnaire focus on arm and hand movements, thereby maximizing the relationship with the HLJT. However, although the MIQ-RS has shown to be a reliable and valid measure for motor imagery ability (Gregg et al., 2010) and is also developed specifically for use in the stroke population (Butler et al., 2012) we did make some adjustments to the protocol that could have influenced our results. Because not all stroke patients were able to complete all movements physically, all participants had to watch a demonstration of the intended movement instead of performing the movement themselves. Therefore, we cannot be sure that all participants did indeed use an internal motor imagery strategy. It could be that by observing a demonstration of the movements our participants were more inclined to imagine movements from an external perspective.

Indeed, a recent study (Williams et al., 2011) showed that observation of movements could facilitate the ease with which movements are imagined. In their study observation of a movement shortly before a participant had to imagine a movement led to higher MIQ scores only when the perspective of the observed and to be imagined movement were congruent with each other. Hence, it could be that in our set-up with the experiment leader sitting next to the participant that participants were more inclined to use an external perspective and as such may have experienced more difficulty imagining the movement from the first person perspective. However, the test conditions were the same for control participants. Therefore, we believe this could hardly explain the differences found on the MIQ-RS in our study. For follow up studies, to better control for these issues, it would be better to use the MIQ3. The MIQ-RS, as is also pointed out by Roberts et al. (2008), cannot distinguish between the internal and an external visual motor imagery perspective. In the new version of the MIQ-RS, the MIQ3 (Williams et al., 2012), external, internal and kinesthetic components are assessed separately.

Williams et al. (2011) also showed that motor experience could influence how easily a movement is imagined. Although, in our study we controlled for this by following the same protocol for control participants and patients it could be that differences in motor experience still had an influence on the ease with which movements could be imagined. Control participants, unlike patients, clearly have had more chance at performing these movements more recently and more frequently than stroke patients. This could have resulted in lower scores in stroke patients compared to controls. However, our scores were similar to that of other studies. We showed a high internal reliability, comparable to those of the original questionnaire (Gregg et al., 2010). Moreover, we did see a difference between the visual and kinesthetic scale, the visual imagery score was higher than the kinesthetic imagery score, both in stroke patients as well as in healthy controls. These results are comparable to studies with the original MIQ-RS and point to a certain degree of sensitivity to dissociate between visual and kinesthetic imagery ability (Butler et al., 2012). Also, a study by Confalonieri et al. (2012) showed comparable scores to our results in a neuroimaging study of stroke patients where the MIQ-RS was also used.

It could be that our patients adopted different strategies than controls for solving the HLJT. For instance, a recent study with stroke patients by Daprati et al. (2010) showed that patients can in some cases adopt alternative strategies, for example use a visual imagery strategy, for solving the HLJT. However, in our study patients, like controls, showed longer reaction times for biomechanical awkward stimuli and this effect was not seen on the reaction time distributions of the visual imagery task. The longer reaction times for more awkward orientations indicate that patients and controls employed the same strategy in the HLJT and that indeed implicit motor imagery was used.

Interestingly, when looking at the individual patients our results are somewhat heterogeneous. Seven patients reported that it was hard to feel the imagined actions whereas scoring well above chance on the HLJT. Five of these patients also found it hard to imagine seeing the imagined action indicating simultaneous impairment of visual and kinesthetic motor imagery. However, one patient (patient 5) also showed an interesting pattern of results. This patient was selectively impaired on the kinesthetic component of the adapted MIQ-RS. Moreover, this patient scored at around chance level on the HLJT. This patient's performance on the HLJT could not be explained by mental slowing because performance on the simple choice task was normal. This patient also scored well above chance on the visual imagery task, suggesting intact visual-spatial capacity. The fact that his kinesthetic ability was selectively below the cut-off score simultaneously with a selective impairment on the HLJT without showing other imagery deficits suggests that to some extent correspondence between conscious experience and implicit ability of motor imagery is also possible after stroke.

At the same time the heterogeneous results in our patients show that the assessment of motor imagery ability in stroke patients is a complex task. The patients that found it very hard to imagine movements might not be able to benefit from mental practice because of the emphasis in mental practice on wilful conscious modulation of motor imagery. On the other hand, this might suggest that these patients, because of their intact implicit motor imagery ability, might still benefit from probing the action system covertly, for instance by observing actions or implicit learning. Given the recent research results on the differences between implicit and explicit learning (see Dew and Cabeza, 2011 for a discussion) makes this question certainly seem worthwhile to explore in more detail. In this respect Holmes and Calmels (2008) have reviewed potential problems for motor imagery based mental practice in the sport setting and have suggested that with an observation based approach some aspects of the covert use of our action system can be better controlled, a direction possibly also worth exploring further in the domain of stroke.

Most motor imagery instruments are originally developed en validated in young healthy populations. For instance, although the original developers of the MIQ-RS adapted the instrument for use in a rehabilitative setting (Butler et al., 2012), there are only a few studies reporting results using the new MIQ-RS with stroke patients. Stroke patient are a far more heterogeneous population than the healthy young adults and this makes interpretation of the results of motor imagery instruments in stroke patients difficult. This is particularly important because in stroke patients the severity and extend of the hemiparesis can be complicated by the presence of neuropsychological deficits in these patients. Deficits in working memory, apraxia, depression, motivational problems, (motor) neglect and anosognosia are all know in some instances to complicate the hemiparesis (Gialanella and Mattioli, 1992; Paolucci et al., 1996; Pohjasvaara et al., 2002; Malouin et al., 2004) and it is likely that the same is true for performance on motor imagery measures, explicit and implicit.

For instance Malouin et al. (2004) showed that performance of motor imagery practice is related to working memory capacity. Furthermore, recent studies on neglect after stroke show a more differentiated picture of different forms and types of neglect. For instance, motor neglect is often under recognized but can influence motor performance (Punt and Riddoch, 2006) and patients can have neglect selectively for near space (peripersonal) as well as for far space (extrapersonal) and for specific modalities (see Halligan et al., 2003 for a discussion). The notion of neglect affecting extrapersonal and peripersonal space differently is akin to the dissociation between first person and third person imagery. A limitation of our study is that we screened patients for neglect, however, we did not control for all the different types of neglect leaving open the possibility that more specific neglect types were undetected and influenced the patients test outcome. In the same regard, other specific neuropsychological deficits could influence motor imagery test performance and the possibilities for and adherence with mental practice regimes. Future studies that systematically study the relationship of neuropsychological disorders with motor imagery ability could greatly enhance our knowledge in this respect.

Another limitation of our study was that we only used two measures for motor imagery. By including other type of measures, such as mental chronometry tasks, prospective action judgment task and also including phenomenological self-reports that are aimed at measuring other subjective components of the imagery process we could be able to further our understanding of how the different components of motor imagery ability relate to each other. A better understanding of the type of impairment of the action system by using different methods and instruments ranging from implicit to explicit, self-rating, physiological, neuropsychological and chronometric instruments, could potentially lead to a better differentiated treatment tuned to the patients characteristics in particular.

Conclusively, our study shows that in stroke patients implicit and explicit motor imagery can be differently affected. The subjective experience of the ease of imagining a movement does not have to be related to implicit motor imagery ability after stroke. Given the recent advocacy for the use of screening instruments to assess motor imagery ability of patients before they enter rehabilitation programs (Braun et al., 2006, 2013 in this issue; Malouin et al., 2013 in this issue) these results have an important clinical application and suggest that screening procedures based solely on subjective instruments could risk excluding patients whose motor imagery ability might still be intact. Our results articulate the complex relationship between the phenomenological conscious experience of motor imagery and use of motor imagery in individual patients and caution the use of one tool as an instrument for use in screening, selecting and monitoring stroke patients.

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A standardized motor imagery introduction program (MIIP) for neuro-rehabilitation: development and evaluation

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Background: For patients with central nervous system (CNS) lesions and sensorimotor impairments a solid motor imagery (MI) introduction is crucial to understand and use MI to improve motor performance. The study's aim was to develop and evaluate a standardized MI group introduction program (MIIP) for patients after stroke, multiple sclerosis (MS), Parkinson's disease (PD), and traumatic brain injury (TBI).

Methods: Phase 1: Based on literature a MIIP was developed comprising MI theory (definition, type, mode, perspective, planning) and MI practice (performance, control). Phase 2: Development of a 27-item self-administered MIIP evaluation questionnaire, assessing MI knowledge self-evaluation of the ability to perform MI and patient satisfaction with the MIIP. Phase 3: Evaluation of MIIP and MI questionnaire by 2 independent MI experts based on predefined criteria and 2 patients using semi-structured interviews. Phase 4: Case series with a pre-post design to evaluate MIIP (3×30 min) using the MI questionnaire, Imaprax, Kinaesthetic and Visual Imagery Questionnaire, and Mental Chronometry. The paired *t*-test and the Wilcoxon signed-rank test were used to determine significant changes.

Results: Data of eleven patients were analysed (5 females; age 62.3 ± 14.1 years). Declarative MI knowledge improved significantly from 5.4 ± 2.2 to 8.8 ± 2.9 ($p = 0.010$). Patients demonstrated good satisfaction with MIIP (mean satisfaction score: $83.2 \pm 11.4\%$). MI ability remained on a high level but showed no significant change, except a significant decrease in the Kinaesthetic and Visual Imagery Questionnaire score.

Conclusion: The presented MIIP seems to be valid and feasible for patients with CNS lesions and sensorimotor impairments resulting in improved MI knowledge. MIIP sessions can be held in groups of four or less. MI ability and Mental Chronometry remained unchanged after 3 training sessions.

Keywords: motor imagery introduction program (MIIP), CNS lesion, sensorimotor impairments, mental practice, stroke, multiple sclerosis, Parkinson's disease

INTRODUCTION

Motor imagery (MI) is defined "as a dynamic state, during which the representation of a given motor act is internally rehearsed within working memory without any overt motor output" (Decety and Grezes, 1999). It is assumed that action planning, action preparation, action simulation, and action observation share similar neuronal substrates (Decety and Grezes, 1999).

MI as a technique to improve motor performance and function has evolved in sports psychology (Start, 1964), where a positive effect of MI training on motor performance had been confirmed (Casby and Moran, 1998; Smith et al., 2001; Guillot et al., 2010). More than 20 years ago, MI as a therapeutic concept has been implemented into neurorehabilitation for patients with sensorimotor impairments. The idea was to have an additional instrument besides the classical therapies to re-establish motor function (Warner and McNeill, 1988). The advantage for patients has been the opportunity to train affected body parts already at an early stage of rehabilitation, when physical movement was not yet possible. As an additional advantage patients have been able to train safely in absence of a therapist, and to fill spare time in the clinical routine with an effective intervention.

Since the beginning of this millennium, a growing body of research has been conducted to test the efficacy of MI interventions in neurorehabilitation (Barclay-Goddard et al., 2011; Schuster et al., 2011). So far, results of this research have been ambiguous (Ietswaart et al., 2011; Braun et al., 2012; Schuster et al., 2012a), likely due the following reasons: the number of patients included in the majority of studies has been too small to draw solid conclusions, and the heterogeneity between patient characteristics and intervention designs was too large to allow for meaningful comparisons. Furthermore, it is difficult to assess MI objectively due to its "concealed nature" (Guillot and Collet, 2005; Malouin et al., 2008a) and comparison of study results is hampered due to different MI ability assessment tools used (Malouin et al., 2008b; Schuster et al., 2010).

There is consensus, that MI interventions are cognitively complex and challenging (Braun et al., 2008; Bovend'eerdt et al., 2010; Ietswaart et al., 2011; Schuster et al., 2012b). Different frameworks for clinical implementation and practice have been published (Braun et al., 2008; Bovend'eerdt et al., 2010). Furthermore, a single MI training session can vary in different elements, such a position, location, and instruction type (Schuster et al., 2011). The twenty different MI training session elements, described in the literature (Schuster et al., 2011), were developed based on the PETTLEP approach published by Holmes (2001). Some of these elements are highly abstract and require a certain level of cognitive ability to be understood by patients or study participants. For example, MI can be rehearsed in different sensory modalities, such as kinesthetic or visual (Schuster et al., 2011). Furthermore, the patient can take an internal and external perspective (Schuster et al., 2011). Thus, without a clear and standardized introduction or familiarization, MI can be interpreted and practiced in different ways by researchers, study participants, or patients. This could jeopardize the validity of study results and the outcome of therapeutic interventions.

Despite the awareness of the complexity of MI (Heremans et al., 2012; Madan and Singhal, 2012), so far little attention has been paid to the introduction and familiarization process of patients or study participants to the concept of MI prior to a MI intervention. Only 19 of 133 studies included in the literature review about best practice in MI by Schuster et al. mentioned an introduction or familiarization element as part of their MI intervention (Schuster et al., 2011). None of these studies examined the introduction or familiarization as an independent MI training session element. In the absence of a standardized introduction or familiarization session prior to an MI intervention, it could be hypothesized that patients and study participants lack important information that would help them to understand the complexity of MI. This may lead to decreased compliance and to a feeling of excessive demands (Bovend'eerdt et al., 2010; Schuster et al., 2012b). Therefore, it is essential that patients or study participants are carefully introduced to the concept of MI before they are tested or start with MI training programs. To improve MI understanding and the basic MI performance skills declarative and procedural knowledge have to be transferred (Annett, 1996). Declarative knowledge involves "knowing the rule," whereas procedural knowledge focuses on "applying the rule" (Nickols, 2010). This knowledge might enable patients or study participants to complete MI assessment tests based on reliable knowledge and to start MI training. A solid basis that allows generating comparable data is equally important for clinical practice as for research interventions. In other fields such as low back pain and endodontic, standardized programs for knowledge transfer have been developed and evaluated and have shown to be effective for knowledge increase (Meng et al., 2009; Sorrell et al., 2009; Foltran et al., 2012).

Therefore the aim of this study was the development and the evaluation of a MI introduction program (MIIP) to familiarize patients with sensorimotor impairments due to central nervous system (CNS) lesion with the concept of MI, to transfer important knowledge and therefore, to improve the understanding of the MI concept, to teach basic MI skills, and to increase the self-perception of the skill to perform MI. Our hypothesis was that MIIP would increase patient knowledge about MI, improve self-perception of the skill to perform MI and result in a good overall satisfaction with MI. Furthermore, it was of interest whether such a pre-training program would change MI ability.

METHODS

The project was divided into four phases: (1) MIIP development, (2) MIIP questionnaire development, (3) Pre-evaluation of the MIIP and the MIIP questionnaire, and (4) Evaluation of the MIIP in a patient pilot trial. An overview of the complete study process is shown in **Figure 1**. The study was approved by the local ethics committee (Ethikkommission Kanton Aargau Switzerland, Reference number: 2012/050) and was conducted in accordance with the Declaration of Helsinki and Good Clinical Practice guidelines. The study was conducted in a neurorehabilitation center in Northwestern Switzerland and study patients were recruited from the clinic internal database according to their diagnosis.

PHASE 1: DEVELOPMENT OF THE MOTOR IMAGERY INTRODUCTION PROGRAM (MIIP)

The objective of this phase was the development of a standardized MIIP in German to improve declarative and procedural knowledge about MI in patients with CNS lesions and sensorimotor impairments. To reach this aim, two main issues were regarded as important. First, the content of the program had to be based on published literature and on current best MI practice. Secondly, the collected information had to be presented in a form appropriate for patients with CNS lesions and sensorimotor impairments with the intention to support the knowledge transfer process.

To find out more about current introduction practice, a content analysis and data extraction regarding the details of the MI training session element familiarization was performed for all 19 studies in the review by Schuster et al. (2011) that mentioned a familiarization or introduction session prior to the investigated MI intervention (Clark, 1960; Van Gyn et al., 1990; Etnier and Landers, 1996; Shambrook, 1996; Casby and Moran, 1998; Smith et al., 2001; Dickstein et al., 2004; Kornspan et al., 2004; Liu et al., 2004a; Reiser, 2005; Sidaway and Trzaska, 2005; Dunsky et al., 2006; Yoo and Chung, 2006; Immenroth et al., 2007; Braun et al., 2008; Bovend'eerdt et al., 2009, 2010; Malouin et al., 2009; Hemayattalab and Movahedi, 2010). Subsequently, the corresponding authors of these 19 studies were contacted and asked to provide detailed information about their introduction or familiarization protocol, respectively. Nine authors responded (Sonnenschein, 1990; Casby and Moran, 1998; Dickstein et al., 2004; Liu et al., 2004b; Sidaway and Trzaska, 2005; Dunsky et al., 2006; Braun et al., 2008; Bovend'eerdt et al., 2010; Hemayattalab and Movahedi, 2010) and three of them provided additional information (Casby and Moran, 1998; Liu et al., 2004b; Sidaway and Trzaska, 2005) that was also analyzed. Furthermore, a search for new literature in PubMed using the terms [Motor AND

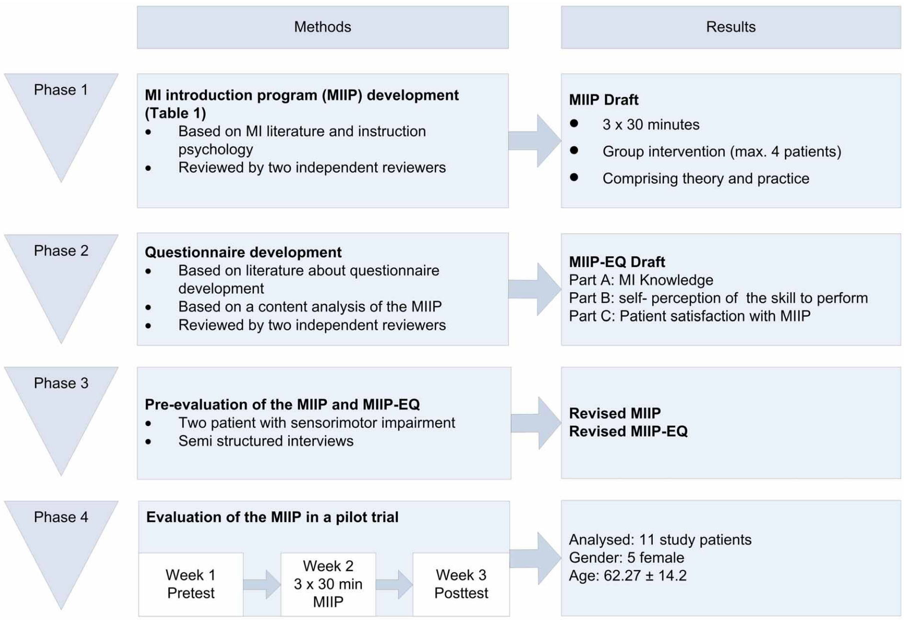

FIGURE 1 | Study phases.

imagery AND familiarization] and [mental AND practice AND familiarization] for the period of 2010/5 to 2011/12 was done, which revealed no additional studies except the one by Schuster et al. (2011).

The theory of teaching psychology was employed for two reasons (Marzano, 1988; Klauer and Leutner, 2012a,b): (1) To ensure that the structure and the instruction mode of the MIIP would support the processing and retrieval of the collected information in patients with CNS lesions and sensorimotor impairments and (2) to increase patients' level of declarative and procedural MI knowledge. A combination of a meaningful verbal form of learning defined by Ausubel and a discovering form of learning defined by Brunner was chosen (Edelmann and Wittmann, 2012). This approach supports motivation and active engagement. For the MIIP this meant that old but unconscious experience with MI in the study patients had to be discovered and linked to new knowledge and that the program had to start with simple topics progressing to more complex tasks at the end. Based on the collected information and the clinical expertise in the neurorehabilitation center a first draft of the MIIP was developed and reviewed by two external experts of the MI field. Eventually, the final MIIP was modified based on their comments and will be described in the following section.

The motor imagery introduction program (MIIP)

The MIIP consists of three introduction/familiarization sessions of 30 min each. The sessions can either be provided as group or single patient intervention. For motivational (Gauthier et al., 1987) and economic reasons the group format is to be preferred. To allow individualized instructions, a maximum of four participants per group is recommended. The program is designed for patients with sensorimotor impairments such as stroke, Parkinson's disease (PD), multiple sclerosis (MS), and traumatic brain injury (TBI). To meet the cognitive demands of the program, patients are required to have a mini-mental state examination (MMSE) Score of more than 20 points and must be capable of reading and understanding German.

The program comprises MI theory (definition, type, mode, perspective, planning) and MI practice (performance, control). In each session, information is presented using power point presentations. All the three sessions have the same structure to simplify orientation. To ensure standardized sequences, detailed information for the instructors is included for each slide. Instructors have to be either physiotherapists or occupational therapists with at least 2 years of work experience with patients with sensorimotor impairments as well as profound knowledge and experience with MI. Depending on group size only a minimum of material is required: a room for group meetings with a table and chairs, a computer with a beamer, stopwatches, pencils, cups, and drinking water. An additional instructor manual provides detailed information about the goal of the program, inclusion criteria for participants, theoretical MI background, required MI knowledge of the staff, format and material used, as well as the media and preparation required for each session. Furthermore, the manual includes an overview table for each session, showing the content and the underlying theory for each slide in chronological order. A minimum of preparation time before/after each session is required.

Session 1. First the study patients learn, that the goal of the MIIP is to familiarize them with the concept of MI and that the

MIIP serves as a standardized pre-training before individualized MI training in combination with classical therapy starts. Study patients learn that MI is the ability to mentally simulate actions and movements; that this ability has been used in sports as a technique to improve motor performance for a long time and that over the last two decades this concept has become more and more popular in neurorehabilitation. They learn that the concept is widely used in clinical routine, but still lacks sound scientific evidence. They learn how MI is believed to function in a very simplified manner. Study patients are prompted to link this theory to their own (preferably positive) experiences and a first standardized practical MI exercise is performed: lifting up a cup from the table and bringing it to the mouth and drink. Afterwards, study patients are asked to repeat this exercise until the next session. To support their MI practice, an instruction sheet describing the home exercise is provided. At the end of each session a summary is given to consolidate the new knowledge.

Session 2. At the beginning there is a brief repetition of the content of the previous session. Then, study patients have the opportunity to share their experiences with their home exercises. In the theoretical part of session two, patients learn that MI in neurorehabilitation is used as an additional therapy to the classical active therapies. They also learn that the goal of MI is to increase motor performance and that MI is a possible treatment technique for all patients who have a basic ability to perform MI. They learn that MI can be performed everywhere as soon as the technique is mastered even in the absence of a therapist. They learn that the technique is not physically exhausting, but that they need to be alert and be able to concentrate to the mental representation of a given movement or action. Then the terms “modality” and “perspective” are introduced and explained with pictures and rehearsed practically. With the new knowledge, the exercise instructed in session one is repeated and the patients now have the possibility to share their own perceptions. At this point a second movement is chosen by the patient and individualized according to his situation. Each study patient receives a second instruction sheet describing his individualized exercise. Session two is concluded with a summary of the new session content.

Session 3. The session starts with a repetition and sharing of experiences at the beginning and a summary of the new content at the end of the session. In the theoretical part of session three the patients learn that MI can be used throughout the day, whenever the time is right for the patient and that no special material is needed. They learn more about details of the process, such as starting- and endpoint of an imagined movement, as well as the necessity to control the mental process. Furthermore, patients learn about and experience different qualities of these mental representations and how they can be described. With the new knowledge, patients have the opportunity to mentally practice their individualized exercise. At the end of session three there is time for group reflection and a short summary of the most important components of the program: the **what**, **who**, **where**, **when** and **how** of MI. A summary of the content of each session is provided in **Table 1**.

Table 1 | Content summary of each MIIP session.

Nr.	Theory	Practical exercises	Assignment
1	• Overview of the content • What MI is • How MI works • Since when MI is being used in NR • Summary at the end of the session	• Link to own experience • First standardized exercise	Instruction sheet with standardized exercise
2	• Repetition and sharing of experience • MI goals in NR • Who can benefit from MI • Where and how MI can be executed • Terms “perspective” and “modality” are introduced • Summary at the end of the session	• Repetition of standardized exercise • Individualized exercise	Instruction sheet with individualized exercise
3	• Repetition and sharing of experience • When MI can be used • Material needed • Starting- and endpoint of one MI trial • Necessity to control the mental process • Group reflection and summary	• Practice of individualized exercise	

NR, neurorehabilitation; MI, motor imagery.

PHASE 2: DEVELOPMENT OF THE MIIP-EVALUATION-QUESTIONNAIRE (MIIP-EQ)

The objective of Phase 2 was the development of a self-administered, paper-based questionnaire in German as an instrument to evaluate the MIIP that was developed in Phase 1. Based on literature about program evaluation and questionnaire construction (Bühner, 2006; Clasen, 2010), and after a content analysis of the MIIP, a first draft of the MIIP-EQ was developed consisting of three parts: A, B, and C. Part A was designed to assess declarative knowledge, part B to assess procedural knowledge with the self-perception of the skills to perform MI, and part C to assess patient-satisfaction. For part C the “Zufriedenheit-8” questionnaire (ZUF-8), an existing questionnaire about patient satisfaction with 8 items in German served as information source (Schmidt et al., 1989). Six questions could be adopted with minor modifications and four more MIIP specific questions were added. For all the three subscales, items in form of questions were developed: part A: 16 items, part B: 10 items, part C: 15 items. For face validity, the same two external experts, who had reviewed the MIIP, also evaluated the preliminary MIIP-EQ collection of items regarding their relevance and to delete or add items if necessary. Based on the results of the external reviewing process and on own clinic expertise, the MIIP-EQ draft was modified and finalized: part A: 12 items, part B: 5 items, part C: 10 items.

In the final version, part A of the MIIP-EQ consisted of 12 multiple-choice questions. For each of the questions, four answers were given (one correct and three false). Each correct answer received a score of 1, for a wrong answer the score was 0. This resulted in a total knowledge score of 12 if all answers were correct (range 0–12). Three questions tested basic knowledge about MI, such as the meaning of MI, the goal of MI and MI processing in the brain in a simplified manner. Two questions asked about the practical execution of MI. Three questions focused on modality and perspective, and one question tested possible terms used to describe the quality of perceived MI. A further question evaluated knowledge about mental chronometry and time equivalence when performing MI compared to physical practice. The content of the individual questions is presented in an abbreviated form in **Table 2**. For the evaluation of the knowledge transfer process the minimal score level to be sufficient was set at eight to ten (60% to 87%) correct answers. Twelve and eleven correct answers were regarded as excellent (88% to 100%). Seven or less correct answers were regarded as insufficient ($< 60\%$). This was in accordance with the censoring model proposed by Klauer and Leutner (2012a,b).

Part B of the MIIP-EQ consisted of five questions regarding different aspects of the skill to perform MI, e.g., during therapy sessions or at home. The patients were asked to evaluate their self-perception on an ordinal ranked unipolar six point Likert scale. The anchors were "very low" at the left end and "very good" at the right end. The total score of part B was 25 points (range 0–25).

Part C of the MIIP-EQ was only part of the post assessment and evaluated the participants' satisfaction with the MIIP. The study patients could rate their satisfaction with the MIIP on an ordinal ranked unipolar six point Likert scale. The anchors were "not at all satisfied" and "very satisfied." Originally, this part consisted of ten questions. Due to an incorrect formulation problem, one question had to be excluded during the analysis. The total score of the revised part C was therefore 45 points (range 0–45). An accept satisfaction level was set at 80% of the maximum $\left(\text{Patient satisfaction} = \frac{\text{patient score}}{\text{maximal possible score}} * 100\right)$, in accordance with literature on measuring patient satisfaction (Wüthrich-Schneider, 2000).

Table 2 | MIIP-EQ part A: correct answers per item for all study patients.

Item-Nr.	MIIP-EQ part A: items asked Abbreviated answer content	Number of correct answers *n* (%) Pretest	Posttest
1	Meaning of the term MI	7 (63.6%)	8 (72.7%)
2	Meaning of the term modality	3 (27.3%)	7 (63.6%)
3	Different qualities of MI modality: kinesthetic/visual	1 (9.1%)	9 (81.8%)
4	Meaning of the term MI perspective: internal/external	1 (9.1%)	5 (45.5%)
5	Description of the quality of MI	3 (27.3%)	10 (90.9%)
6	Simplified theory about the mechanism of MI	4 (36.3%)	7 (3.6%)
7	Goal of MI	10 (90.9%)	11 (100%)
8	Correct performance of one MI trial	7 (63.6%)	9 (81.8%)
9	Different phases of MI per trial: planning, execution, controlling	6 (54.5%)	5 (45.5%)
10	MI ability after central nervous system lesion	6 (54.5%)	6 (54.5%)
11	Advantages and benefits of MI	10 (90.9%)	9 (81.8%)
12	Definition of mental chronometry	1 (9.1%)	8 (%)

MI, motor imagery; MIIP-EQ, motor imagery introduction program evaluation questionnaire.

PHASE 3: PRE-EVALUATION OF MIIP AND MIIP-EQ

The objective of Phase 3 was to test the understandability of the MIIP and the MIIP-EQ in two pilot study patients. Inclusion criteria were sensorimotor impairments such as stroke, PD, MS, TBI, age older than 18 years, a MMSE score of more than 20 and the capability of reading and understanding German. Exclusion criteria were the presence of more than one of the above-mentioned diagnoses and previous experience with MI. Two inpatients met the inclusion criteria, one with MS, and one patient after stroke. After receiving oral and written information about the pre-evaluation and signing an informed consent form, they underwent the MMSE screening and were then included. In two separate single subject sessions (1.5 h per session), the study patients were introduced to MIIP and the MIIP-EQ draft. After each session, a semi-structured interview was conducted, covering the following areas: comprehensibility of the entire MIIP and MIIP-EQ, as well as comprehensibility of each MIIP slide and of MI specific terms after explanation. The answers were recorded and written notes were taken. The study patients had mainly comments regarding technical terms. They felt overwhelmed by the amount of MI specific terminology. Based on this information the drafts of the MIIP and the MIIP-EQ were revised. All technical terms, which were not absolutely necessary for patients or study participants in order to understand MI, were replaced by plain language terms.

PHASE 4: EVALUATION OF THE MIIP

The objective of the last phase was to evaluate the MIIP in a pilot trial. Our hypothesis was that MIIP would (a) increase the declarative knowledge about MI, (b) improve procedural knowledge about MI measured with the self-perception of the skill to perform MI, and (c) result in a good overall satisfaction with The MIIP. Furthermore, it was of interest whether such a program would change MI ability.

Study patients

The study was conducted at the rehabilitation center Rheinfelden. Between October and December 2012, inpatients as well as outpatients from the clinic were invited to participate in the study according to their diagnoses. The same eligibility criteria as in the pre-evaluation (Phase 3) were applied. After receiving oral and written information and signing the informed consent form, 12 study patients were screened for meeting inclusion criteria/eligibility. All 12 study patients were eligible and underwent pretest assessment. Information about age, gender, educational level, duration of the impairments, living situation, dominant and affected side and other therapies was recorded. One study patient did not complete the study due to a norovirus infection. His data was not included in the final data analysis. Eleven study patients underwent posttest assessment.

Procedure

Different parameters regarding MI were assessed before and after the MIIP. In study week 1, the study patients were screened and underwent pretest assessment. All assessments were performed by two physiotherapists, which had been trained by an MI expert of the clinic. In study week 2, the MIIP, consisting of 3 × 30 min introduction sessions (as described above in the "program development" section) was conducted. After finalization of MIIP in study week 2 or 3 all posttest assessments were performed by two physiotherapists, who had not been involved in the instruction of the MIIP. Approximately 1.5 h were used for pre-and post-assessments. Additionally, patients' comments regarding the MIIP were noted/recorded in an open unstructured form. Due to recruitment the first group consisted of 3 participants, the second of 1 participant, the third of 3, the fourth of 2 and the fifth of 3 participants ($n = 12$).

Outcome measures

The primary outcome and secondary outcomes and corresponding measures are described in **Table 3**.

The MIIP-EQ is described in detail in Phase 2 "development of the MIIP-Evaluation-Questionnaire (MIIP-EQ)" mentioned above.

The KVIQ has specifically been developed for patients after stroke (Malouin et al., 2007) and was re-validated after translation into German for patients with sensorimotor impairments (Schuster et al., 2010). To assess MI ability, the KVIQ-G 20 measures both the perceived clarity and the perceived intensity of a given movement during imagination in a standardized way using a visual and a kinesthetic subscale. Patients have to imagine a set of standardized movements, involving the whole body and each side of the body. The movement is demonstrated once by the assessor. After a single execution of the movement, patients are asked to take an internal perspective, to imagine the movement and to rate the clarity and intensity of each mental picture on a 5 point-Likert-scale (clarity: 1 = "no image," 5 = "image as clear as actually seeing it"; intensity: 1 = "no sensation," 5 = "as intense as performing the movement"). The KVIQ exists in a short and a long version, with 10 questions (KVIQ-G 10) or 20 questions (KVIQ-G 20), respectively (maximum score: 100 points; range 20–100 points). To calculate subscale scores as well as the total score, the values of 10 specified items for each subscale (visual and kinesthetic) are summed up.

Imaprax-G is a standardized, computer and video based test to assess MI ability. It has specifically been developed for patients with apraxia after stroke (Fournier, 2000) and was re-validated after translation into German (Schuster et al., 2010). The test consists of six upper limb gestures presented in different video sequences. For each gesture, the understanding, the clarity of the mental representation of the movement, and the perspective taken are assessed. The clarity can be rated on a 7 point Likert scale, ranging from 1 (vividness worse than in all of the presented video sequences) to 7 (vividness better than in all of the presented video sequences, maximum score 42 points, range 6–42 points).

Mental chronometry is a reliable and valid instrument to measure the congruency between the time needed to imagine a specific movement and the time needed to actually perform the same movement (Malouin et al., 2008b). A high MI ability results in an almost perfect congruence and a ratio close to 1. For standardization the following movement was chosen: "grasp a cup, lift it up, and bring it to the lips," because all the included study patients were able to perform this movement. Each study patient had three attempts. For each attempt, first, the movement was performed and then the image of the same movement was generated. With a stopwatch the assessor measured the time needed to perform the movement and the time needed to perform the imagination in seconds. Study patients indicated the beginning and the end of each imagined movement by nodding their heads.

Table 3 | Primary and secondary study endpoints and corresponding outcome measures.

Primary study endpoint	**Primary outcome measure**
Change of declarative knowledge about MI	Part A of the MIIP-EQ: Knowledge score (max. score 12 points, range 0–12 points, 6-point Likert scale)
Secondary study endpoints	**Secondary outcome measures**
Change of procedural knowledge about MI	Part B of the MIIP-EQ: self-perception of MI performance skills (max. score 25 points, range 0–25 points, 6-point Likert scale)
Study patient satisfaction with MIIP	Part C of the MIIP-EQ (max. score 45 points, range 0–45 points, 6- point Likert scale)
Change in the MI ability	$KVIQ_{vis}$-G 20 and $KVIQ_{kin}$-G 20 (max. score 50 points, range 10–50 points for each subscale) Imaprax-G vividness total score (Imaprax-Software, Version 1.1) (max. score 42 points, range 6–42 points)
Change in mental chronometry ratio	Change in the time congruence between the time needed to imagine a specific movement and the time needed to actually perform the same movement, expressed as: ratio = $\frac{\text{I=time to imagine the movment (s)}}{\text{E=time to execute the movement (s)}}$

MIIP, motor imagery introduction program; MIIP-EQ, motor imagery introduction program evaluation questionnaire; KVIQ, kinesthetic and visual imagery questionnaire; G, German.

STATISTICS

For all analyses the Statistical Package for the Social Sciences (SPSS, IBM Inc.) version 20 was used. Patient characteristics and baseline data were analyzed using descriptive statistics. Differences between pre- and posttest results were compared using the following statistical tests for depended data: (1) Parametric data with a normal distribution (assessed with the Kolmogorov-Smirnov-Test) were analyzed using the paired *t*-test (Part A of the MIIP-EQ). (2) Non-parametric data (Part B and C of the MIIP-EQ, Imaprax and KVIQ) and not normally distributed data (mental chronometry) were tested using the Wilcoxon signed-rank test. The level of significance was set at $p = 0.05$.

RESULTS

DEMOGRAPHICS

The demographics of the study patients are reported in **Table 4** and an overview over the raw scores is given in **Table 6**.

PRIMARY OUTCOME: IMPROVEMENT OF DECLARATIVE KNOWLEDGE ABOUT MI AFTER THE MIIP: (MIIP-EQ PART A)

The declarative knowledge score improved significantly from 5.4 ± 2.2 to 8.8 ± 2.9 ($p = 0.010$). The mean difference was 3.5 ± 3.6 (min -3, max $+10$) points. Nine study patients could improve their knowledge after the MIIP. Only one patient showed a negative result (difference -3 points) and one showed no change in declarative knowledge. Four study patients achieved excellent results with 11 or 12 correct answers. Three study patients achieved sufficient results with 9 or 10 correct answers. Four study patients showed insufficient results with 7 or less correct answers. The numbers of correct answers per item for all study patients is given in **Table 5**. An overview on the individual study patient results in the pretest- and posttest assessment is provided in **Table 6**. Statistical results are provided in **Table 7**.

SECONDARY OUTCOMES

Change of procedural knowledge about MI after the MIIP (MIIP-EQ part B)

The procedural knowledge about MI measured with the elf-evaluation of the MI performance skill (MIIP-EQ, part B) changed non-significantly from 16.2 ± 4.3 to 18.5 ± 2.4 ($z = -0.721$, $p = 0.47$). The mean increase was 2.3 ± 5.6 points (range from -2 to $+16$). Five study patients rated their skill to perform MI in the posttest assessment lower than in the pretest assessment (difference -2 in 3 study patients, difference -1 in 2 study patients) and one study patient showed no change. An overview of the results for each study patient is displayed in **Table 6**. Statistical results are provided in **Table 7**.

Study patient satisfaction with the MIIP (MIIP-EQ part C)

The mean total satisfaction score was 37.5 ± 5.2 (range 28–44) or $83.2 \pm 11.4\%$, i.e., above the level of 80% defining good satisfaction. Interestingly, the two study patients with the lowest MMSE also showed the lowest satisfaction score with the MIIP. An overview of the results for each study patient is shown in **Table 4**. The mean satisfaction score per item is reported in **Table 5**.

KVIQ-G 20

There was no significant change in the visual subscale of the KVIQ-G 20 ($z = -1.424$, $p = 0.153$). The kinesthetic subscale of the KVIQ-G 20 decreased significantly ($z = -2.004$, $p = 0.045$). Results of the KVIQ-20 for each study patient are shown in **Table 6**. Statistical results are provided in **Table 7**.

Imaprax-G

There was no significant change in the vividness score ($z = -0.341$, $p = 0.733$). All results for each study patient are shown in **Table 6** and an overview over the statistical results is reported in **Table 7**.

Mental chronometry

There was no significant change in mental chronometry ($z = -0.178$, $p = 0.86$). At pretest, mean time to perform MI was 3.3 ± 2.1 s (range 1.5–8.6 s). Mean time to physically perform

Table 4 | Demographics.

Patient number ($n = 11$)	Mean/*SD*
Gender (female/male)	$f = 5$
Age (years)	62.3 ± 14.2
More affected body side (right/left)	$r = 4$
Duration of impairments (months)	111 ± 142
MMSE	28.4 ± 1.5

MMSE, mini-mental state examination score.

Table 5 | Patient satisfaction scores of MIIP part C (possible range 0–5).

Item-Nr.	Abbreviated content	mean ± *SD* ($n = 11$)	% of maximum
1	Satisfaction with the overall quality of the MIIP	3.8 ± 0.9	76
2	Satisfaction with the fulfillment of expectations	3.8 ± 1.0	76
3	Satisfaction with the organization of the MIIP	4.0 ± 0.5	80
4	Satisfaction with the comprehensibility of the MIIP	4.6 ± 0.7	92
5	Perceived stress during the MIIP: No stress = 5/high stress = 0	4.6 ± 0.7	92
6	Satisfaction with degree of individualization during the MIIP	4.4 ± 0.7	88
7	Satisfaction with MI ability after the MIIP	4.2 ± 1.0	84
8	Emotional well-being during the MIIP	4.2 ± 1.0	84
9	Willingness to practice with MI after the MIIP	4.2 ± 1.0	84

MIIP, motor imagery introduction program; max, maximum percentage.

Table 6 | Row scores of each patient.

Patient number ($N = 11$)	Pat. 1	Pat. 2	Pat. 3	Pat. 4	Pat. 5	Pat. 6	Pat. 7	Pat. 8	Pat. 9	Pat. 10	Pat. 11
DEMOGRAPHICS											
Gender (female/male)	f	f	m	m	m	m	m	f	f	m	f
Age (years)	70	76	40	52	68	75	45	43	69	72	75
Diagnosis	Stroke	Stroke	MS	TBI	Stroke	Stroke	Stroke	MS	MS	PD	MS
More affected body side (right/left)	r	l	r	l	l	l	l	r	l	r	r
Duration of impairments (months)	2	4	290	1	8	63	1	192	420	60	180
MMSE	28	28	28	29	28	30	30	29	30	25	27
MIIP-EQ QUESTIONNAIRE											
MIIP-EQ: knowledge pretest (range 0 to 12)	5	3	4	6	2	4	9	7	7	4	8
MIIP-EQ: knowledge posttest (range 0 to 12)	6	7	12	10	12	9	12	9	11	4	5
Difference MIIP knowledge (range −12 to +12)	1	4	8	4	10	5	3	2	4	0	−3
MIIP-EQ part B pretest(range 0 to 25)	14	18	5	20	18	17	20	14	20	17	15
MIIP-EQ part B posttest (range 0 to 25)	21	16	21	18	16	19	21	21	19	16	15
Difference MIIP-EQ (range −25 to +25)	7	−2	16	−2	−2	2	1	7	−1	−1	0
MIIP-EQ: Patient satisfaction (range 0 to 45/%)	40/89	35/78	35/78	40/89	39/87	44/98	40/89	37/80	44/98	30/67	28/62
IMAPRAX-G CLARITY PRETEST (RANGE 6–42)	34	35	32	30	25	35	36	36	36	33	34
gesture 1: to beckon somebody (identified gesture/level of clarity/perspective used)	P/5/E	P/5/E	P/5/E	T/3/E	T/4/I	P/6/E	T/6/E	P/6/I	P/6/E	P/6/I	F/6/E
gesture 2: to cut something	F/6/E	T/6/E	T/5/I	T/4/I	T/5/I	T/6/E	T/6/I	T/6/I	T/6/I	T/6/E	T/6/E
gesture 3: to write something	P/6/E	P/6/E	T/5/E	P/6/E	P/4/I	P/6/I	T/6/I	T/6/I	T/6/I	T/6/E	P/6/E
gesture 4: to brush one's teeth	T/6/E	T/6/E	T/6/E	T/6/E	P/5/E	P/6/E	T/6/E	T/6/I	T/6/E	T/5/E	T/6/E
gesture 5: to cock a snook	T/6/E	T/6/E	T/6/E	P/5/E	T/3/E	T/5/E	T/6/E	T/6/I	T/6/E	T/6/E	T/4/E
gesture 6: to applaud somebody	T/5/E	T/6/E	T/5/E	T/6/E	T/4/I	T/6/E	T/6/I	T/6/I	T/6/E	T/5/E	T/6/E
IMAPRAX-G POSTTEST (RANGE 6–42)	36	35	36	35	29	34	36	36	36	29	27
gesture 1: to beckon somebody	P/6/E	P/6/E	T/6/E	T/5/E	T/5/E	P/5/E	T/6/I	T/6/I	P/6/E	T/3/I	T/4/E
gesture 2: to cut something	T/6/E	T/6/E	T/6/E	T/6/E	T/5/E	T/6/E	T/6/I	T/6/I	T/6/E	P/5/E	T/4/E
gesture 3: to write something	T/6/E	P/6/E	T/6/E	T/6/E	T/4/I	T/5/I	T/6/I	T/6/I	T/6/E	P/6/E	P/6/E
gesture 4: to brush one's teeth	T/6/E	P/6/E	T/6/E	T/6/E	T/5/E	T/6/E	T/6/I	P/6/I	P/6/E	F/5/E	P/5/E
gesture 5: to cock a snook	T/6/E	T/5/E	T/6/E	T/6/E	T/6/E	T/6/I	T/6/I	T/6/I	T/6/E	T/6/E	T/2/E
gesture 6: to applaud somebody	T/6/E	T/6/E	T/6/E	T/6/E	T/4/I	T/6/I	T/6/I	T/6/I	T/6/E	P/4/I	T/6/E
MENTAL CHRONOMETRY PRETEST											
Mean MI time of 3 attempts (s)	1.7	8.6	3.2	2.1	5.2	2.2	1.5	3.3	1.6	3.5	3.0
Mean movement time of 3 attempts (s)	3.7	7.5	3.5	1.4	2.8	2.1	1.2	2.4	2.1	5.6	2.9
Ratio	0.5	1.2	0.9	1.5	1.9	1.1	1.2	1.4	0.8	0.6	1.0
MENTAL CHRONOMETRY POSTTEST											
Mean MI time of 3 attempts (s)	2.4	10.6	4.3	1.1	4.7	5.3	2.7	2.6	3.0	3.0	2.6
Mean movement time of 3 attempts (s)	4.8	7.3	3.7	1.6	2.4	6.7	3.8	2.1	3.8	2.3	2.3
Ratio	0.5	1.4	1.2	0.7	2.0	0.8	0.7	1.3	0.8	1.3	1.2
KVIQ-20 CLARITY TEST											
KVIQ-20 pretest (10–50)—vis. subscale	39	29	38	39	33	42	46	10	47	31	44
KVIQ-20 posttest (10–50)—vis. subscale	39	26	38	38	31	39	47	40	42	28	39
KVIQ-20 pretest (10–50)—kin. subscale	43	39	37	31	24	22	39	15	46	32	41
KVIQ-20 posttest (10–50)—kin. subscale	37	38	36	29	27	12	36	20	36	26	30

MS, multiple sclerosis; TBI, traumatic brain injury; PD, Parkinson's disease; MMSE, mini-mental state examination score; MIIP-EQ, motor imagery introduction program evaluation questionnaire; P, partially true; F, false; T, true; E, external; I, internal; KVIQ, kinesthetic and visual imagery questionnaire.

the movement was 3.2 ± 1.9 s (range 1.2–7.5 s). Pretest ratio was 1.1 ± 0.4 (range 0.5–1.9).

At posttest assessment, mean time to perform MI was 3.9 ± 2.6 s (range 1.2–10.6 s). Mean time to physically perform the movement was 3.7 ± 1.9 s (range 1.6–7.3 s). Posttest ratio was 1.1 ± 0.5 (range 0.5–2). Results of each individual study patient are shown in **Table 6** and an overview over the statistical results is reported in **Table 7**.

Open patient comments

In general the study patients were very interested in the program. They participated actively and contributed to a

Table 7 | Statistical results.

	Mean/*SD*		Median (range)	*z*-value	*p*-value
MIIP-EQ QUESTIONNAIRE					
MIIP-EQ: knowledge pretest (range 0–12)	5.4 ± 2.2	3.5 ± 3.6			$p = 0.014$
MIIP-EQ: knowledge posttest (range 0–12)	8.8 ± 2.9				
MIIP-EQ part B pretest(range 0–25)	16.2 ± 4.3		17 (5–20)	−0.721	$p = 0.471$
MIIP-EQ part B posttest (range 0–25)	18.5 ± 2.4		19 (15–21)		
MIIP-EQ: Patient satisfaction (range 0–45/%)	37.5 ± 5	83.2 ± 11.4%			
Imaprax-G clarity pretest (range 6–42)	33.27 ± 3.3		34 (25–36)	−0.341	$p = 0.733$
Imaprax-G clarity posttest (range 6–42)	33.6 ± 3.5		35 (27–36)		
KVIQ-20 CLARITY TEST					
KVIQ-20 pretest (10–50)—vis. subscale	36.2 ± 10.5		39 (10–47)	−1.424	$p = 0.153$
KVIQ-20 posttest (10–50)—vis. subscale	37 ± 6.2		39 (26–47)		
KVIQ-20 pretest (10–50)—kin. subscale	33.6 ± 9.7		37 (15–46)	−2.004	$p = 0.045$
KVIQ-20 posttest (10–50)—kin. subscale	29.7 ± 8.2		30 (12–38)		
MC pretest Mean MI time of 3 attempts (s)	3.3 ± 2.1	Ratio 1.1 ± 0.4	1.05 (0.47–1.85)	−0.178	$p = 0.859$
MC pretest Mean movement time: 3 attempts (s)	3.2 ± 1.9				
MC posttest Mean MI time of 3 attempts (s)	3.9 ± 2.6	Ratio 1.1 ± 0.5	1.16 (0.49–1.97)		
MC posttest Mean movement time: 3 attempts (s)	3.7 ± 1.9				

MIIP-EQ, motor imagery introduction program evaluation questionnaire; MC, mental chronometry; KVIQ, kinesthetic and visual imagery questionnaire; s, seconds.

good atmosphere during the group sessions. Six of the study patients mentioned a personal benefit from the program. The perceived personal benefit concerned functional improvements, e.g., dressing, selective range of motion in four and better MI abilities in five study patients. Two of them mentioned that kinesthetic MI is difficult for them to practice, and two others mentioned that the pace of the program could have been higher.

DISCUSSION

Although, there is consensus in the literature that MI is a cognitively complex and challenging concept (Lotze and Halsband, 2006; Schuster et al., 2012a), familiarization has so far not been regarded as a key element of MI. A familiarization process has not been standardized or systematically evaluated. The aim of our study was to develop a standardized MIIP for patients with a CNS lesion and sensorimotor impairments, with the intention to improve their declarative and procedural knowledge about MI and to evaluate this MIIP in a pilot trial.

The whole process was structured into four phases: in phase one the MIIP and in phase two the corresponding evaluation questionnaire (MIIP-EQ) were developed. In phase three these two elements were pre-evaluated and modified and in phase four the revised versions were evaluated in a pilot patient trial.

During the development process of the MIIP was distinguished between declarative and procedural knowledge (Annett, 1996). The MIIP was designed for practical use in clinical routine. A manual for therapists was created to facilitate implementation of the whole program into clinical practice or its use in clinical studies. With only 3 × 30 min instruction time and a minimum of preparation time, overall time expenditure is well manageable. Group size can be varied between one and four patients, offering great flexibility to fit the program to different clinical situations and busy patient schedules.

The MIIP-EQ was developed to guarantee an objective MIIP evaluation. Three different aspects were regarded as important to be evaluated: (1) the success of the intended declarative and (2) procedural knowledge transfer, and (3) patient satisfaction.

The pre-evaluation phase proved to be important to detect incomprehensibilities in the MIIP and the MIIP-EQ, saving both personal and patient resources and improving quality of the data generated in the pilot trial.

In the pilot trial, we found that the MIIP significantly increased declarative MI knowledge in the majority of our study patients. This finding supports the hypothesis that the MIIP is a feasible tool to transfer declarative MI knowledge in patients with sensorimotor impairments. After the MIIP, the majority of the study patients showed a sufficient to excellent level of declarative MI knowledge (Klauer and Leutner, 2012a,b). It can be assumed that consequent implementation of such a structured instruction program would enhance the clinical benefit that patients could derive from MI, but this would need to be tested in an adequately designed clinical trial.

However, even after the MIIP, still a majority of the study patients could not link the word "perspective" to the words "external and internal," and detecting the correct phases of one MI sequence remained difficult. This may have two reasons: Either there was not enough emphasis on this fact during the sessions or the perspectives as a construct are too complex to understand for some patients. This raises questions about what patients are doing when they are asked to take a certain perspective to perform MI either in test situations or in therapy. Since this is crucial for obtaining valid MI assessment results and for being able to practice MI in the future, more attention has to be paid to these aspects. When applying the MIIP in our clinic, we decided to put more emphasis on this by having patients describe the perspective they have taken.

In only two out of eleven patients declarative MI knowledge did not improve. Additionally, both patients also rated lowest on the absolute posttest knowledge score. Interestingly, the same two patients had the lowest MMSE scores (25 and 27 points, respectively) in the screening examination. The observation that knowledge gain in the context of a complex concept such as MI requires a relatively high level of cognitive abilities should be taken into account for future research on MI and the clinical applications of MI.

The hypothesis that the level of procedural knowledge would significantly increase after the MIIP was not supported by our results. The self-perception of the skill to perform MI showed no significant improvement after the MIIP. Five patients even rated their skill to perform MI in the posttest assessment lower than in the pretest assessment. A possible explanation for this could be that with better declarative knowledge of the MI concept after the MIIP, some patients might have rated their skill to perform MI more accurately than at the beginning (where they might have overestimated their true skill level). This could have disguised a possible beneficial effect of the MIIP (Schuster et al., 2010). Again, the two study patients with the lowest MMSE scores at screening also showed the lowest scores in the self-perception of the skill to perform MI. This may indicate that a low level of declarative knowledge negatively influences procedural knowledge, although the results do not consistently show this. Based on these observations it can be proposed that MMSE performance should be considered to allocate patients to different MI group levels. This could help to meet the different demands of patients with varying cognitive abilities. In this respect, our results are in accordance with the findings of other investigators, who had observed that even after MI training barriers remained that compromised the motivation of the patients to practice MI (Bovend'eerdt et al., 2010). To promote the concept of MI, factors that negatively influence self-perception of the skill to perform MI or the motivation of the patient to practice MI, such as limited cognitive capacity, should be systematically evaluated in future studies. Overall, study patients were satisfied with the MIIP. However, the two study patients with the lowest MMSE scores also showed the lowest satisfaction scores. It seems that patient satisfaction can only be influenced to a certain level by external parameters. It can be assumed that increasing discrepancy between cognitive ability of the patient and the demand of the program will raise the level of frustration and negatively impact satisfaction scores.

All measured parameters regarding MI ability did not change significantly after the MIIP, supporting their retest reliability. However, the total score of the KVIQ kinesthetic subscale did change significantly toward a reduction in MI vividness. The significant difference is in accordance with findings of another study (Schuster et al., 2010) and supports the fact that with improved understanding of the concept, self-rating becomes more accurate.

Of special interest are the two patients, who scored lowest on the posttest knowledge score, in the self-perception of the skill to perform MI and the patient satisfaction, but showed relatively high scores in the MI ability questionnaires. It remains unclear, how they rated for example their kinesthetic sensations, without having a cognitive construct of the underlying theory and without a basic understanding of the terms used. This supports the idea that MI ability has to be assessed with a number of tools to get a more comprehensive idea of the patient's true MI ability.

Limitations

A limitation of the MIIP and the MIIP-EQ development process was, that it did not try to reach consensus among the MIIP developer and the reviewers. However, this would have required a lengthy Delphi procedure, which was not justifiable considering the limited resources and the overall impact of the study question. Since there is no generally accepted standard MIIP that could have been used as gold standard, the authors did not use a control group in our pilot trial. As there is no plausible reason why patients should have gained knowledge just by chance, the increase in knowledge seen in this study can be attributed to the MIIP. A limitation of the MIIP-EQ was that it was solely developed for this study and was therefore not tested for its psychometric validity. The validity of the pilot trial is limited by the small sample size and the great heterogeneity between study patients regarding age, diagnoses, and onset of the impairment. This makes statistical interpretations difficult. However, it should be realized, that in clinical practice such heterogeneity is encountered and therefore the included study patients represent a "real world sample" thus strengthening external validity of the study findings. A further limitation was the lack of a follow up examination to determine for how long the gained knowledge can be maintained, and whether this gain in knowledge translates into a clinical benefit such as improved outcome for the patients.

CONCLUSIONS

It can be concluded that the developed MIIP is a feasible intervention to introduce and familiarize patients with the included diagnoses and with sufficient cognitive abilities to the concept of MI. With the MIIP there is now an instrument available that is easy to use and might help to introduce patients to the MI concept and to prepare them for MI training. This may improve long-term motivation and adherence.

So far there is no validated assessment tool available that is easy to handle and allows to objectively measuring mental capacity and cognitive abilities that are required for successful learning of MI. The clinical implication is that patients need to be observed very closely during their initial phase using MI. Upon this clinical possibility it has to be decided whether the patient is able to learn and perform MI with a potential benefit. This is in accordance with the statements of different other authors (Braun et al., 2008; Bovend'eerdt et al., 2012).

For the future, the possibility that low MMSE scores negatively affect the familiarization process should be evaluated in more detail. It should be analyzed what component of the different cognitive abilities, such as perception, attention, memory, motor, language, visual/spatial, execution, interferes most with a successful acquisition of MI ability. So far required MMSE scores in published MI trials showed a wide range going for example from 15 to 24 (Crosbie et al., 2004; Malouin and Richards, 2010; Schuster et al., 2012a). It might be assumed that higher cognitive abilities than previously thought are required to allow acquisition of the basic declarative and procedural MI knowledge. Furthermore, the correlation between a good introduction to MI and long-term benefits in terms of knowledge, motivation, and functional outcomes should be investigated in a randomized controlled trial.

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Mental representation and motor imagery training

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Research in sports, dance and rehabilitation has shown that basic action concepts (BACs) are fundamental building blocks of mental action representations. BACs are based on chunked body postures related to common functions for realizing action goals. In this paper, we outline issues in research methodology and an experimental method, the *structural dimensional analysis of mental representation* (SDA-M), to assess action-relevant representational structures that reflect the organization of BACs. The SDA-M reveals a strong relationship between cognitive representation and performance if complex actions are performed. We show how the SDA-M can improve motor imagery training and how it contributes to our understanding of coaching processes. The SDA-M capitalizes on the objective measurement of individual mental movement representations before training and the integration of these results into the motor imagery training. Such motor imagery training based on mental representations (MTMR) has been applied successfully in professional sports such as golf, volleyball, gymnastics, windsurfing, and recently in the rehabilitation of patients who have suffered a stroke.

Keywords: mental representation, mental imagery, motor imagery, mental simulation, basic action concepts

The representation and simulation of motor acts has a long and varied history in psychology and movement science. Johann Friedrich Herbart related movements to perceptual effects as early as 1825 and proposed that the imagery of perceptual effects can elicit the related movements (p. 464). William James (1890, p. 526) wrote some decades later "that every representation of a movement awakens in some degree the actual movement...". These and other approaches of an ideomotor understanding of human action felt out of fashion in the era of behaviorism (see Shin et al., 2010 for a review). However, around 100 years later they became an important reference point for many experimental approaches, for example, *ideomotor action* (e.g., Knuf et al., 2001; Kunde, 2001; Koch et al., 2004; Kunde et al., 2004), *common coding* (Prinz, 1987, 1997), *anticipative behavioral control* (Hoffmann, 1993; Hoffmann et al., 2004), *theory of event coding* (Hommel et al., 2001) and *cognitive architecture of action approach* (Schack and Mechsner, 2006; Schack and Ritter, 2009). These approaches underline the goal-directedness of human behavior (termed "motor cognition" by Jeannerod, 2006, p. v) and are considered an alternative to non-cognitive approaches to human movement.

These new perceptual-cognitive perspectives emphasize the goal-directedness property of actions, the importance of anticipated perceptual effects, the crucial role of mental representations in action control and the functional role of mental simulation for planning and performing voluntary movements with the help of structured cognitive representations of action effects (Hommel et al., 2001; Mechsner et al., 2001; Schack and Mechsner, 2006; Hoffmann et al., 2007). Furthermore, skillful coordination occurs if appropriate mental representations of the motor task and action goals are constructed, because cognitive representations govern the tuning of motor commands and muscular activity patterns. In fact, this perceptual-cognitive approach to movement control is reminiscent of some classical ideas in psychology, such as the "ideomotor" approach adopted by Lotze (1852) and James (1890) in the 19th century and the theoretical studies of movement construction by Bernstein (Bernštejn) (1947, English translation 1967) in the 20th century. Although this perspective never disappeared, it was obscured by the dominant and competitive perspectives of cognitive and dynamical systems approaches to motor control.

Whereas dynamical systems in principle try to explain biological movements without alluding to cognitive levels (or internal models), Bernstein (Bernštejn) (1947) envisaged a complex architecture of human movement control ranging from "low" levels corresponding to involuntary movements, up to "high" cognitive levels that can be thought of as concepts. The second "lowest" level corresponds to synergistic processing, and this level has often been referred to in dynamical systems approaches (e.g., Wolpert et al., 1995; Ijspeert et al., 2002). We note that spinal (e.g., D'Avella and Bizzi, 1998; Poppele and Bosco, 2003) and some muscle synergies do not always require input from higher cognitive levels (e.g., Debicki and Gribble, 2005). Such aspects of involuntary movements are often addressed in sensorimotor models of motor control (e.g., Kawato, 1999; Todorov, 2004). These processes run mostly automatically but can reach conscious levels if attention is directed towards them. In stark contrast to "low" levels, our understanding of *cognitive* movement control is far less known. Therefore, in this paper, we have focused on "higher" (i.e., cognitive) levels of human motor control (perceptual-cognitive approach), and suggest that cognitive representations should be differentiated from cognitive *control* of movements (cf. Schack, 2004a,b, 2010). That is, our approach is more closely related to cognitive approaches for motor control such as Schmidt's classical schema theory[1] (Schmidt, 1975) and is in competition with dynamical system approaches. However, we do not suggest that motor control, or even voluntary movements, are solely controlled from a cognitive level. Involuntary motor control (e.g., reflexes and postural control) are also critically important as sensorimotor loops. We will discuss how cognitive levels of movement representation and control can be measured and used for (training) interventions. Among the key issues are how structured mental representations can arise during motor skill acquisition and how these representations attain a functional role in motor learning. Related questions concern the role of cognitive representations in motor imagery training and, prospectively, whether motor imagery can be applied to technical platforms and robotics.

MENTAL REPRESENTATION

It is a well established idea in cognitive psychology and indeed it has received growing acceptance in the fields of motor control and sport psychology that actions are mentally represented in functional terms as a combination of the executed action and the intended or observed effects (Prinz, 1997; Hommel et al., 2001; Knuf et al., 2001; Koch et al., 2004; Jeannerod, 2006, p. 165). The link between movements and perceptual effects is bi-directional and is thought to be stored hierarchically in long-term memory (LTM). Such movement representations are necessary because complex movements are highly unlikely to rely solely on online calculation due to human resource limitations. Rosenbaum and co-workers (Rosenbaum et al., 2007) demonstrated that movements can be understood as a serial and functional order of goal-related body postures, or goal postures, and their transitional states. That is, movements can be understood as the changes between body postures. Whereas body postures (keyframes) are represented in detail, the interframes (i.e., the movements between body postures) contain only differences between two successive keyframes. The better the order formation within cognitive movement representations, the more easily information can be accessed and retrieved (Schack and Ritter, 2009). This leads to increased motor execution performance, which reduces the amount of attention required for successful performance (Beilock et al., 2002; Raab and Johnson, 2007; Land et al., 2014). The nodes within such networks of movement representation contain functional subunits or building blocks that relate motor actions and associated perceptual effects.

Researchers from different fields, such as cognitive psychology, cognitive robotics and sport psychology (Schack, 2004a,b; Schack and Mechsner, 2006; Schack and Ritter, 2009, 2013; Tenenbaum et al., 2009; Maycock et al., 2010), have provided evidence for so-called basic action concepts (BACs) in the control of human movements. Analogous to the well-established notion of basic object concepts (Rosch, 1978), BACs are the mental counterparts of functional elementary components of complex movements. They can be thought of as the cognitive chunking of body postures and movement events concerning common functions in realizing action goals. BACs do not refer to behavior-related invariant properties of objects, as in the case in basic object concepts, but to perception-linked invariant properties of movements. According to the cognitive action architecture approach (Schack, 2010), mental representations are thought to comprise of such representational units (i.e., BACs) and their structural composition in relation to one another.

To investigate representational networks of BACs, the *structural dimensional analysis of mental representation* (SDA-M) method was developed by Schack (2004a). Various methods facilitate the study of knowledge-based mental representations of movements in LTM (for an overview, see Hodges et al., 2007). However, most of them focus on explicit knowledge and are non-experimental (e.g., interviews, questionnaires, paper-and-pencil tests). As an experimental method that avoids introspective statements, Schack (2004a, 2010) introduced the SDA-M method. This method provides psychometric data on mental representations of complex movements and as such permits investigating the status and change of structures of mental movement representations.

In detail, the SDA-M (Schack, 2010) maps mental representations as integrated networks of BACs across both individuals and groups, by providing information on relational structures in a given set of concepts with respect to goal-oriented actions. The internal grouping of conceptual units (i.e., the clustering of BACs) delineates the structure of the knowledge representation of a certain movement. While mental representation structure refers to the relation and the grouping of BACs in LTM, learning can be considered as the modification of the mental representation structure over time. That is, mental representation of complex movements can be measured by the SDA-M method.

The SDA-M consists of four steps (for further details, see Schack, 2012). First, a split procedure involving a multiple sorting task (pair-wise comparisons) delivers a distance scaling between BACs of a suitably predetermined set. Specifically, during this procedure, one concept of a given set of BACs is permanently displayed on a computer screen (anchor concept) and all other concepts are compared to that anchor concept successively. Participants have to decide whether the two given concepts are related to each other during movement execution. The procedure continues, until all concepts have been compared to all other concepts. Second, a hierarchical cluster analysis is used to transform the set of BACs into a hierarchical structure. Third, a factor analysis reveals the dimensions in this structured set of BACs, and fourth,

[1]According to the Schmidt's Schema Theory, each skill action we have learned needs its own individual motor program stored in LTM. Schmidt suggested that we need 3 things to perform a skill: A generalized motor program as the basic form of our movements, like a forehand drop shot that can generate a variety of similar actions under different circumstances, e.g., shots at a variety of heights. A Recall Schema to adjust the generalized motor program for a particular action (e.g., a forehand drop at a particular height) after understanding the actual situation (initial conditions) and the intentions (response specification). When the movement is performed, the sensory consequences (e.g., feel of the movement) and response outcomes (e.g., flight path of the shuttlecock) are stored in memory. This is the so called Recognition Schema used to evaluate the outcome of the movement (response outcome) and to detect errors. If the response outcome is not perfect, the schemas are modified based on sensory feedback and knowledge of results. This leads to further adjustments of the generalized motor program when practicing a movement in order to subsequently achieve the desired outcome.

the cluster solutions are tested for invariance within or between groups.

As a result, one obtains the individual partitioning of the BACs in hierarchical tree-like structures, the so-called dendrograms (see **Figure 1**). Cluster solutions are calculated for all individual participants and for the whole group. Each cluster solution is established by determining a critical Euclidean distance d_{crit} (marked by the dotted horizontal line in **Figure 1**). The critical value d_{crit} depends on the number of concepts. All junctures below the value d_{crit} are considered related, while the junctures above this value are considered unrelated. This results in a cluster solution. In an optimal structure, the resulting cluster solution represents the functional phases of the movement.

A good example to investigate the mental representation structures of a complex movement on different levels of expertise is the tennis serve (Schack and Mechsner, 2006). For a tennis serve, not only many degrees of freedom have to be controlled in the musculoskeletal system, but also the correct movement execution depends considerably on training and expertise. On the other hand, it is a finite and recognizable action pattern of which the overall structure is well defined by biomechanical demands.

The expert group in that study consisted of 11 male tennis players (mean age, 24 ± 3.7 years) from the upper German leagues who were ranked between places 15 and 500 in the German men's rankings. The non-player group were 11 males (mean age, 24 ± 6.7 years) with virtually no experience of the game (maximum 5 h) and had never had any tennis lessons.

The single BACs and the adequate functional organization of the tennis serve were characterized in advance in collaboration with non-players, athletes with different levels of expertise, and coaches. Photographs of the tennis sub-movements were presented to experts and non-players together with linguistic markers of varying generality. The picture-word combination which took the shortest time to judge its appropriateness was chosen, in analogy to classical methods (Rosch, 1978).

Each BAC was characterized by a set of closely interconnected sensory and functional features. For example, BAC 7 (whole body stretch motion) is functionally related to providing energy to the ball, transforming tension into swing, stretching but remaining stable. Afferent sensory features of the corresponding submovement that allow monitoring of the initial conditions are bent knees, tilted shoulder axis, and body weight on the left foot. Reafferent sensory features that allow monitoring of whether the functional demands of the sub-movements have been addressed successfully are muscles stretched and under tension, proprioceptive and, finally, perhaps visual perception of the swinging arm and ball in view.

Figure 1A depicts the dendrogram for the experts. Their cognitive structure was very similar to an optimal cluster solution and matches the functional and biomechanical demands of the tennis serve. The three functional phases (i.e., pre-activation, strike, and final swing) form clearly separated clusters in the dendrogram. An invariance analysis (step four of the SDA-M) confirmed this interpretation. There was no significant difference between the cognitive BAC framework in experts and the biomechanical demand structure of the movement. In contrast, the clustering of the BACs in the dendrogram of the non-players (**Figure 1B**) did not mirror the functionally and biomechanically demanded phases so well. The BACs were less clearly grouped, with no close neighborhoods, and the partial clusters largely failed to attain significance. The average novice structure, however, deferred significantly from the optimal cluster solution (cf. Schack and Mechsner, 2006). That is, in experts, these representational frameworks were organized in a distinctive hierarchical tree-like structure, were remarkably similar between individuals, and were well-matched with the functional and biomechanical demands of

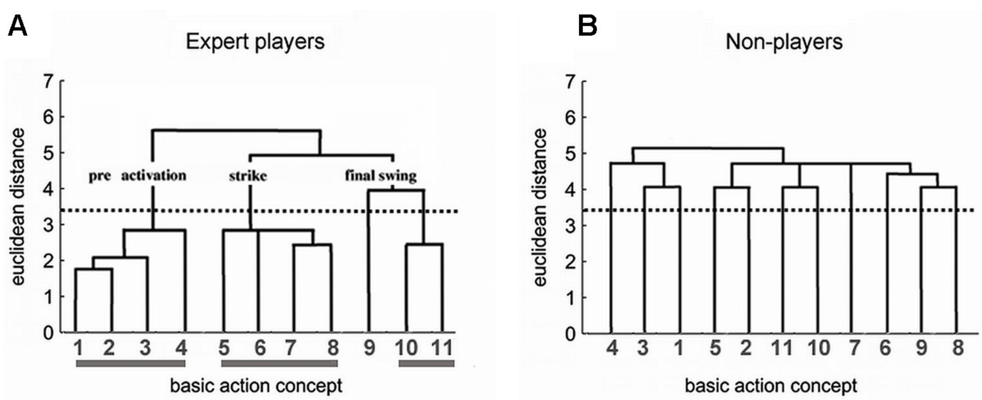

FIGURE 1 | Dendrograms for the experts (A) and non-players (B) based on the hierarchical cluster analysis of BACs in the tennis serve. The horizontally aligned numbers denote the BACs (for the code, see text), the vertical numbers, the euclidean distances. For every group, it holds $n = 11$; $p = 0.05$; $d_{\mathrm{crit}} = 3.46$. A tennis serve consists of three distinct phases, each of which fulfills distinct functional and biomechanical demands. First, in the pre-activation phase, body and ball are brought into position, and tension energy is provided to prepare the strike. The following BACs were identified: (1) ball throw, (2) forward movement of the pelvis, (3) bending the knees, and (4) bending the elbow. Second, in the strike phase, energy is conveyed to the ball. The following BACs were identified: (5) frontal upper body rotation, (6) racket acceleration, (7) whole body stretch motion, and (8) hitting point. Third, in the final swing phase, the body is prevented from falling, and the racket movement is decelerated after the strike. The following BACs were identified: (9) wrist flap, (10) forward bending of the body, and (11) racket follow through.

the task. In contrast, action representations in low-level players and novices were organized less hierarchically, were more variable among persons, and were less well-matched with functional and biomechanical demands.

More generally, if two BACs are frequently classified by participants as being "functionally related" during the split procedure, these BACs are characterized by a small Euclidean distance which is reflected in a low projection of the BACs on the vertical axis in the dendrogram (e.g., BACs 1 and 2 in **Figure 1A**). If two BACs are not judged to be "functionally related", the Euclidean distance is larger and the projection of the two BACs is high in the tree diagram (e.g., BACs 9 and 10 in **Figure 1A**).

In order to measure the inter-individual or inter-group differences between representation structures, a structural invariance measure λ is determined based on (1) the number of constructed clusters of the pair-wise cluster solutions; (2) the number of concepts within the constructed clusters; and (3) the average quantities of the constructed clusters. The invariance measure λ ranges from 0 (no similarity at all) to 1 (tree diagrams are identical). Two cluster solutions (or representation structures) are considered to be invariant (i.e., the same) if $\lambda > \lambda_{crit} = 0.68$ (which corresponds to a significance level of $\alpha = 0.05$; for more detailed information, see Schack, 2010, 2012).

Furthermore, as shown in a volleyball study (Schack, 2004b), these mental representation structures are position- and task-dependent. Such representation structures are the outcome of an increasing, effort-reducing formation of order in LTM. With increasing expertise, the representation of the movement corresponds more and more to its topological (spatiotemporal) structure. Accordingly, movement control becomes possible by representing the anticipated perceptual effects of the movement and comparing them with incoming perceptual effects.

Accordingly, the structure of cognitive representations in LTM is also relevant for perception and visuomotor control in motor action. But little is known about the relationship of cognitive representations and visuomotor control for complex movements. Therefore, in a recent study we investigated whether cognitive representations of complex movements influence (unconscious) visual perception (Güldenpenning et al., 2011). Novices and skilled high-jump athletes were shown to differ in that only skilled athletes have a functionally structured, cognitive representation of the high jump movement (Fosbury flop). Both groups were asked to classify pictures of body postures of the high jump movement. In a so-called priming paradigm, each of these picture presentations were preceded by another picture of a high jump body posture that could not be perceived consciously. Participants had to classify whether the second pictures in each trial showed a body posture from the approach or from the flight phase. Importantly, the two pictures in each trial could differ with regard to the shown movement phase but also in temporal order. That is, both pictures could reflect the natural order within or between movement phases or, alternatively, they could be presented in a reversed order (e.g., flight before approach). We found a main effect of temporal order for skilled athletes, that is, faster reaction times for picture pairs that reflected the natural movement order as opposed to the reversed movement order. Novices showed a qualitatively different data pattern which was in line with superficial processing of visual features unrelated to the high jump movement. These results suggest that the structure of cognitive movement representations modulates the visual processing of body postures. Temporal information seems to be an important dimension of such representations (cf. also Güldenpenning et al., 2013) and can be processed automatically as the extraction of temporal order information required unconscious processing of (one of) the pictures.

Based on these and many other studies (e.g., Haggard and Wolpert, 2005; Giummarra et al., 2007; Bläsing et al., 2010b), we argue that major interfaces in the architecture of movement are cognitive in nature (without fully denying the relevance of automated processes such as reflexes or postural control of the whole body). Such a perspective does not view the motor system as being distinct from cognition. Instead, it considers both conscious and automatized processes of movement organization to be based functionally on cognitive representation structures. This does not ignore the significance of emotional or motivational processes; it simply puts them aside in order to focus on the cognitive architecture of movement (Schack and Ritter, 2009). In the next sections we will consider how mental representations change during motor imagery and motor learning.

MENTAL REPRESENTATION AND LEARNING

Differences in the mental representation structure between novices, intermediates, and experts (Schack and Mechsner, 2006; Bläsing et al., 2009) suggest that the structure of mental representations of complex movements changes with improvements in the skill-level. More specifically, the structure of the mental representation of a given complex movement might develop towards the functional structure of an expert over the course of practice. Therefore, a novice's unstructured representation of a movement is thought to develop into a more structured representation during motor learning. Accordingly, we assume learning to be a product of modifying the mediating structure among the BACs (see Schack, 2004a).

To the best of our knowledge, there are only a few studies examining how mental representation structures develop during practice. As it seems crucial to learn more about whether and when changes in mental representations occur and how they develop during learning, we examined structural changes in mental representations of a complex movement during early skill acquisition (Frank et al., 2013). The acquisition of the golf putting movement was investigated in a group of novice golfers. After a 3 day period of practice with the task, the mental representation of the practice group was compared to that of a control group. As expected, the mental representation structure showed functional changes (i.e., functional clusters in the group's dendrogram) in the practice group along with performance improvement while no such changes were observed in the control group.

Specifically, the mental representation structure of the practice group changed over the course of practice from pre-test (**Figure 2A**) to retention-test (**Figure 2B**) and became more similar to an expert structure. As shown in **Figure 2**, the practice group's mean dendrogram revealed an increased number of functional clusters during retention-test, with BACs being clustered

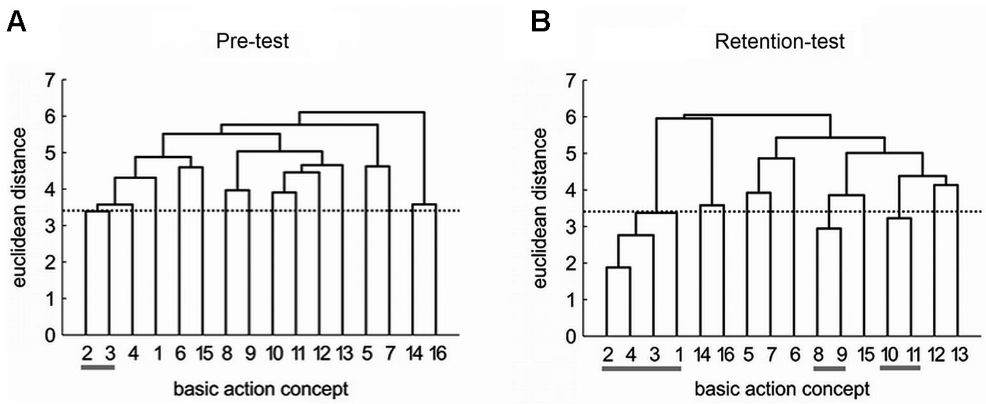

FIGURE 2 | Mean group dendrograms of the practice group (n = 12) for the golf putt at (A) pre-test and (B) retention-test. The numbers on the x-axis relate to the BAC number, the numbers on the y-axis display euclidean distances. The lower the link between related BACs, the lower is the euclidean distance. The horizontal dotted line marks d_{crit} for a given α-level (d_{crit} = 3.41; α = 0.05); links between BACs above this line are considered unrelated; horizontal gray lines below BAC numbers mark clusters. BACs: (1) shoulders parallel to target line, (2) align club face square to target line, (3) grip check, (4) look to the hole, (5) rotate shoulders away from the ball, (6) keep arms-shoulder triangle, (7) smooth transition, (8) rotate shoulders towards the ball, (9) accelerate club, (10) impact with the ball, (11) club face square to target line at impact, (12) follow-through, (13) rotate shoulders through the ball, (14) decelerate club, (15) direct clubhead to planned position, and (16) look to the outcome [Reprinted from Frank et al., 2013, with permission].

into three functional units relating to distinct movement phases (i.e., movement preparation, the forward swing, and the impact phase). In contrast, no changes were evident in the mental representation structure of the control group which did not execute the putt at all. These findings suggest that order formation of action-related knowledge plays a significant role during motor learning, presumably, for the development of movement expertise. Further investigations from a number of different activities (e.g., golf, soccer, wind surfing, volleyball, gymnastics, and dancing) also support the functional relation between mental representation structures and performance and expertise (Schack, 2004a; Schack and Bar-Eli, 2007; Schack and Hackfort, 2007; Bläsing et al., 2009, 2010a; Velentzas et al., 2011).

NEW DIRECTIONS: APPLICATION OF SDA-M IN MOTOR IMAGERY TRAINING

Studies in the first half of the 20th century indicate that performing mental tasks leads to subsequent performance improvements (Sackett, 1935; see also Driskell et al., 1994). Generally, imagery refers to a collection of abilities, including, for example, visual imagery, kinesthetic imagery, imagery of movements or combinations of imagery modalities (e.g., Callow and Hardy, 2005; Holmes, 2007; Roberts et al., 2008) and there continues to be no consensus on the definitions of imagery. In sports, the subject of imagery is traditionally related to movement (i.e., motor imagery, cf. Jeannerod, 1994) and the main aim of motor imagery is to enhance specific motor actions (cf. Boschker, 2001). Studies have shown that specific training can increase the amount and the efficiency of kinaesthetic imagery and enhance the imagery of kinaesthetic sensations, making images more complex and vivid (Nordin and Cumming, 2007; Golomer et al., 2008). Motor imagery is a cognitive tool strategically used by athletes for learning and optimizing their specific movement tasks. Dancers, for example, use motor imagery to exercise the memorization of long sequences and to improve movement quality in terms of spatiotemporal adaptation and artistic expression. Whereas mental practice or mental training encompass further techniques such as self-talk, goal setting or attention focusing, we refer by “motor imagery training” to the act of repeatedly imagining a movement without executing the movement and with the primary intent of acquiring and optimizing motor skills (for an overview see Morris et al., 2005).

Various theories have been used to explain the effects of motor imagery training (or mental practice, e.g., Heuer, 1985; Driskell et al., 1994). The major scientific models largely differentiate physiologically peripheral (neuromuscular) effects and central effects (e.g., symbolic codes or programs). It has been suggested that motor imagery is based on simulation processes that recruit motor representations, and that imagery, observation and execution of movements share a major part of their neural correlates (so-called functional equivalence, Jeannerod, 1995, 2001; Kosslyn et al., 2001). Furthermore, it has been shown that motor imagery involves internal motor attention processes and states of high concentration (Munzert et al., 2008).

Importantly, the *perceptual-cognitive hypothesis* opens up a new explanation for the effects of motor imagery training. This hypothesis is derived from the theory of ideomotor action (Knuf et al., 2001; Koch et al., 2004) and is in line with current neurophysiological findings (Jeannerod, 1995, 2004). The perceptual-cognitive hypothesis posits a representational system in which strong cognitive representation units (nodes) are linked to perceptual representations (e.g., kinesthetic, optical, or acoustic effect codes). Because they possess a spatiotemporal structure, these representations can be related directly to movements. This makes additional motor, spatial-pictorial, or symbolic representations unnecessary for movement control (see Heuer, 1985). Another basic assumption of the perceptual-cognitive model is that imagining a movement and performing it are based on the same representations (Jeannerod, 1995, 2004), which can explain the effectiveness of motor imagery training. Mental simulations of movement may strengthen links between cognitive representation of intermediate states of that movement and the accompanying perceptual effect codes. At the same time, interfering perceptual inputs will be inhibited.

This makes the SDA-M method proposed here directly relevant for developing new forms of motor imagery training (cf. also Cooley et al., 2013). One central question in sport psychology has been the question of how to best tailor and deliver motor imagery training such that it is most effective in enhancing an athlete's performance and in promoting learning. The main disadvantage of traditional procedures is that they try to optimize performance without taking the athlete's mental technique representation into account (i.e., they are representation-blind). If the movement's cognitive representation has structural gaps or errors, these will tend to be stabilized rather than overcome by repeated practice. An alternative method here is to measure the mental representation of the movement before motor imagery training and then integrate these results into the training. Thus, similarly to the finding that imagery tailored to the individual is more promising compared to standardized procedures (for an overview, see Schuster et al., 2011), we suggest that the individual's prerequisites should be considered when applying motor imagery training. As opposed to more subjective measures such as interview techniques, the SDA-M method is an objective measure of BACs and their relations (i.e., mental representation structure). As such, the SDA-M serves to tailor imagery content of subsequent mental practice according the individual's cognitive status. This Motor imagery Training based on Mental Representations (MTMR[2]) has now been applied successfully for several years in professional sports such as golf, volleyball (Schack, 2004b), gymnastics (Schack and Heinen, 2000; Heinen et al., 2002), and windsurfing (Schack and Hackfort, 2007).

To illustrate our approach, consider our recent research in professional volleyball which addressed the spike (i.e., attack hit). This movement requires at least 12 sub-steps (BACs). In preparation for a motor imagery training program, we studied this structure in the members of a Women's Volleyball Youth National Team. **Figure 3** illustrates the results for two players who are both outside hitters.

Player A (**Figure 3A**) was highly skilled in performing the spike movement such that she was able to optimally execute the technique. Accordingly, she held a clearly structured, almost ideal movement representation in her movement memory. BAC 1–3 in connection with 4 and 5 form the *run-up* phase. Concepts 6, 7, and 8 combine for the *hit-preparation* phase, whereas 9, 10, and 11 make up the *hit*-phase.

In contrast, player B (**Figure 3B**) had difficulties in optimally executing the spike for several years. The SDA-M analysis showed a problematic structure in the mental movement representation: BAC 1–3 and 4–5, which are important for the sequence of impulses during run-up and take-off, point to a less precise memory structure. For this player, run-up and take-off were broken down into two inefficient memory sections (5–2 and 4–3, encircled in **Figure 3B**). Subsequently, an individualized motor imagery training program for player B tackled the memory structure and developed motor imagery for an ideal take-off and a proper spike. Additionally, player B went through a series of run-up and take-off drills designed to bring out the optimal motion sequence. The focus was on making the player aware of the altered movement so that she could develop a new feeling for it. We subsequently aimed to generate this optimal *perception* of the movement also in the complementary motor imagery training. This succeeded in improving player B's spike significantly, and she is now a member of the Women's A-National Team. The advantage of this combination of motor imagery training and memory analysis is that athletes' memory structures are integrated into the motor imagery training considering their individual dispositions.

Holmes and Collins (2001) made an important step towards individualized motor imagery training. These authors proposed the so-called PETTLEP approach (Physical, Environment, Task, Timing, Learning, Emotion and Perspective) to motor imagery which stresses the need for functionally equivalent and therefore behaviorally matched imagery interventions as opposed to traditional imagery interventions (e.g., Holmes and Collins, 2001; Smith et al., 2007; Wakefield et al., 2013). That is, the seven PETTLEP aspects of a given movement should be optimized in the sense that they converge between actual and imagined movement execution. This approach is partly rooted in Lang's bio-informational theory (Lang, 1979, 1985) which states that motor imagery training affects motor performance by way of the strengthening of memory representations. Specifically, during imagery, stimulus, response, and meaning propositions[3] are being accessed and thus strengthen the representation of the movement stored in memory, which in turn affects motor performance. Based on findings from neurophysiological research that similar processes are activated during imagined and actual motor actions, Holmes and Collins (2001) suggested that functional equivalence is a major prerequisite for the efficacy of mental practice. Therefore, behavioral matching of the imagined experience to the actual physical experience has been suggested to enhance the efficiency of motor imagery training as it is proposed to best access the underlying motor representation (Holmes and Collins, 2001; Wakefield et al., 2013).

Whereas the PETTLEP approach draws on the matching of the imagined and the actual experience in order to best access the underlying motor representation during motor imagery training, MTMR addresses the mental representation itself as the basis for motor imagery training. That is, a particular movement and its structure are emphasized in MTMR and corrected, if necessary. In that sense, the imagined movement is individually adapted,

[2]Although we focus in this paper on motor imagery rehearsal, the MTMR approach is not restricted to this technique. In the MTMR approach other techniques such as relaxation, cognitive or emotional preparation can be included.

[3]According to Lang (1977, 1985), images are functionally organized sets of propositions. Stimulus propositions reflect the content of the image, response propositions the person's responses to the image, and meaning propositions the interpretations of the image, i.e., its meaning for the person. Response proposition provide a access to the motor command system in order to generate movements. Note that these proposition are conceptualized as having an amodal format (Lang, 1977; Callow and Hardy, 2005).

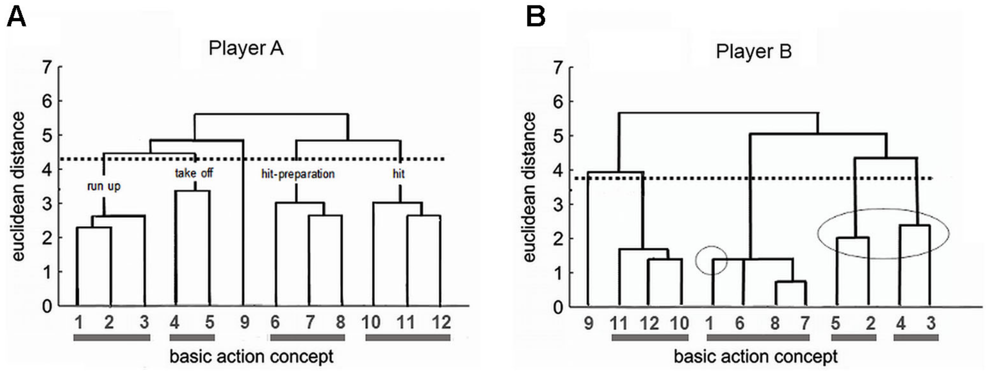

FIGURE 3 | Memory profile of the spike in player A's (A) and player B's (B) movement memory. BACs: (1) taking arms back, (2) stamp step, (3) bending knees and trunk, (4) swinging both arms forward, (5) extending legs, (6) body arching, (7) spiking arm back, (8) high elbow, (9) glance toward opponent's block, (10) spike emphasizing the wrist, (11) whipping extension of arm, and (12) drawthrough of hitting arm. A scale indicating the distances of BAC representations in movement memory is located on the left side of the figure. The lower the value of a horizontal connection between two BACs, the lower the distance between them in movement memory (Printed from: Schack, 2004a, p. 417 with permission).

not only the embedding aspects such as the PETTLEP elements should be optimized. Lang's (1979, 1985) bio-informational theory points to a potential mechanism of how MTMR (employing the SDA-M method) may lead to performance improvements. By emphasizing specific movement phases during motor imagery training, access or retrieval of response and meaning proposition might be facilitated and, thereby, help to improve the structure of the movement representation. It is important to note that the SDA-M method if used in motor imagery training is focused on imagining the movement in its biomechanically and functionally optimal structure.

Motor imagery training is sometimes employed using the SDA-M method by various professional and amateur sports athletes and also in rehabilitation (Braun et al., 2006, 2007; Holmes, 2007; Malouin and Richards, 2013; Malouin et al., 2013 for review) although imagery might be more efficient for stroke patients in chronic stages (Ietswaart et al., 2011). In cases of injury, motor imagery training offers a means of training even when active movement execution is severely impaired. As a result, new opportunities for motor imagery training open up in the fields of medical and orthopedic-traumatologic rehabilitation. Motor imagery training seems to be of great use for regaining lost movement patterns after joint operations (Braun et al., 2006; Holmes, 2007; Malouin et al., 2013). This provides more evidence that motor imagery training provides a general means to link imagery and movement in various areas of life.

EMPIRICAL EVIDENCE: MOTOR IMAGERY TRAINING STUDIES

Velentzas (2010) recently explored the effects of MTMR on volleyball spike performance, and on participants' mental representations of movements. Specifically, the effects of MTMR and generic imagery scripts were investigated. Expert female volleyball players who play the outside hitter position participated. Selected movement characteristics were measured, and mental representations for these movements were evaluated using the SDA-M method. Participants' spike accuracy was also evaluated. To control for participants' imagery ability, the Movement Imagery Questionnaire-Revised (MIQ-R; Hall and Martin, 1997) was used. Results showed an increased performance in the post and retention test for participants in the individualized imagery script group compared to the generic script group. This result suggests that an individualized imagery script which is based on participants' mental representations is more effective than a traditional, generic motor imagery.

Recently, we examined the influence of motor imagery training on the development of mental representation structure in early skill acquisition (Frank et al., 2014). Based on the previous finding (Frank et al., 2013) that mental representation structures functionally adapt during physical practice (i.e., during motor learning), we investigated whether mental practice adds to this adaptation process. For this purpose, novices practiced the golf putt either mentally, physically, or in a combination of both over three days, while a control group did not practice at all. Participants' putting performance and mental representation structures (SDA-M) were tested before and after the intervention and after a retention interval of 72 h. Analyses revealed functional adaptations in mental representation structure together with improvements in putting performance for all groups. Moreover, participants who practiced mentally, either solely or in combination with physical practice, revealed representation structures that were more similar to that of experts than participants who did not practice mentally. This was the case for both, the post-test and the retention-test. These findings support the idea that mental practice in the sense of motor imagery training is beneficial to the cognitive adaptation process during motor learning.

An interesting issue to address in future studies is that of an individual's imagery ability and its relation to the underlying mental representation of a particular motor action in memory. Imagery ability pertains to an individual's general capability to generate and to control an image (for an overview on imagery ability, see e.g., Morris et al., 2005; Cumming and Williams, 2012) and has been found to moderate the influence of motor imagery rehearsal on performance (e.g., Goss et al., 1986; Robin et al., 2007). In this respect, a valuable objective for future research would be to explore the relationship between imagery ability, as measured by the MIQ-R (Hall and Martin, 1997), the revised version of the Vividness of Movement Imagery Questionnaire (VMIQ-2; Roberts et al., 2008), or the Sport Imagery Ability Questionnaire (SIAQ; Williams and Cumming, 2011), and mental representation, as measured by SDA-M in more detail. To explain, although holding the same level of general imagery ability, two individuals may differ on how elaborate their underlying representation of a certain motor skill is (and vice versa). Furthermore, it will be interesting to investigate whether and how MTMR affects imagery ability. Although it is well-known that motor imagery training in general can improve imagery ability (e.g., Rodgers et al., 1991), research has yet to be carried out to investigate the specific influence of MTMR on imagery ability.

POTENTIAL RELEVANCE FOR TECHNICAL FIELDS

An important reason for the new interest in a cognitive-perceptual and architectural understanding of action is the impressive development of cognitive robotics. More research efforts are needed to understand how mental imagery and its mechanisms in human cognition can be applied to enhance motor control. Computational models of various kinds provide starting points to transfer the insights from the role of mental representations and motor imagery training to technical systems to enhance technical motor control in human machine interactions such as humanoid robots. Such computational models are often biologically inspired, that is, they are artificial neural nets (e.g., WALKNET, Cruse et al., 1998; Cruse and Schilling, 2013; Schilling et al., 2013 or echo state networks, Krause et al., 2010). Other cognitive-inspired computational modeling approaches of mental imagery are based on eye-movement research (Farah, 1984; Essig et al., 2012; Sima and Freksa, 2012). Such modeling approaches can reveal engineering principles for the development of autonomous systems that are capable of exploiting the characteristics of mental imagery to interact more efficiently and smoothly with the environment. Furthermore, computational models of motor control can provide novel frameworks for the question of how the central nervous system conjoins sensory signals, mental imagery and motor commands.

CONCLUSIONS

Many theories assume that human action representations functionally integrate motor information and information on action effects. Specifically, perceptual-cognitive approaches claim that motor control comprises representations of target objects, movement characteristics, goals and anticipated disturbances. Here, we have presented a method to objectively evaluate the structure among basic action concepts, the fundamental building blocks of movement representations at the mental level. Reported evidence shows that the structure of movement representations as assessed with the SDA-M is associated with individual skill levels, biomechanical and task constraints and changes through (mental) training. Thus, it is suggested that learning progress can also be monitored by means of the SDA-M method which is an objective way to measure cognitive (movement) representations.

We have reviewed a number of studies that demonstrate the successful application of the SDA-M in professional sports such as golf, dance and volleyball and also in other settings such as rehabilitation after impairments. As the SDA-M permits a reliable, individual diagnostics of movement representations, it provides a valuable tool for individualized motor imagery training and coaching.

The methods presented here make it possible to take the essential information on the underlying cognitive-perceptual action system into account and, thereby, address the individual needs of an athlete in a better way, for example, by using the described Motor imagery Training based on Mental Representation method (MTMR). The theoretical perspective on the construction of action developed here (cf. Schack, 2004a,b), and the SDA-M method could be relevant for optimizing the daily work of the sport psychologist and also for opening up new perspectives to modify approaches to motor imagery training (Schack and Bar-Eli, 2007; Schack and Hackfort, 2007).

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Motor imagery during action observation modulates automatic imitation effects in rhythmical actions

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We have previously shown that passively observing a task-irrelevant rhythmical action can bias the cycle time of a subsequently executed rhythmical action. Here we use the same paradigm to investigate the impact of different forms of motor imagery (MI) during action observation (AO) on this automatic imitation (AI) effect. Participants saw a picture of the instructed action followed by a rhythmical distractor movie, wherein cycle time was subtly manipulated across trials. They then executed the instructed rhythmical action. When participants imagined performing the instructed action in synchrony with the distractor action (AO + MI), a strong imitation bias was found that was significantly greater than in our previous study. The bias was pronounced equally for compatible and incompatible trials, wherein observed and imagined actions were different in type (e.g., face washing vs. painting) or plane of movement, or both. In contrast, no imitation bias was observed when MI conflicted with AO. In Experiment 2, motor execution synchronized with AO produced a stronger imitation bias compared to AO + MI, showing an advantage in synchronization for overt execution over MI. Furthermore, the bias was stronger when participants synchronized the instructed action with the distractor movie, compared to when they synchronized the distractor action with the distractor movie. Although we still observed a significant bias in the latter condition, this finding indicates a degree of specificity in AI effects for the identity of the synchronized action. Overall, our data show that MI can substantially modulate the effects of AO on subsequent execution, wherein: (1) combined AO + MI can enhance AI effects relative to passive AO; (2) observed and imagined actions can be flexibly coordinated across different action types and planes; and (3) conflicting AO + MI can abolish AI effects. Therefore, combined AO + MI instructions should be considered in motor training and rehabilitation.

Keywords: motor simulation, mirror neurons, joint action, mental practice, video therapy, observational learning, stroke rehabilitation, movement demonstrations

INTRODUCTION

Research in action observation (AO) and imitation has made a series of important discoveries since the early 1990s. Traditional paradigms where imitation tasks were explicitly instructed are now complemented by research investigating a broader range of imitation-related phenomena (Heyes, 2013). For example, in naturalistic social settings, interacting partners often exhibit subtle but spontaneous mimicry of each other's behavior, such as their postures, gestures, and speech, typically without knowing or intending to do so (Chartrand and van Baaren, 2009). Research investigating the neurocognitive mechanisms that underpin such imitative behavior essentially shows that watching another person's action primes execution of similar actions in the observer (*visuomotor priming*; for a review see Vogt and Thomaschke, 2007). More recently, this phenomenon has been termed automatic imitation (AI; Heyes, 2011): a type of stimulus-response compatibility (SRC) effect, wherein observing a task-irrelevant action (distractor) facilitates the performance of similar actions and interferes with the performance of dissimilar actions. AI effects typically consist of differences between response initiation times for compatible vs. incompatible distractor actions (c.f., Brass et al., 2000, 2001; Stürmer et al., 2000). In addition, imitation biases can also be demonstrated using kinematic data. For instance, we recently quantified the magnitude of AI effects in the cycle time of compatible and incompatible rhythmical actions (that is, the "kinematic fidelity" of AI, Eaves et al., 2012). In the present research we investigated whether the magnitude of this imitation bias can be modulated by a range of motor imagery (MI) and execution instructions during distractor observation. Next we describe how our previous findings led us to instruct MI *during* AO in the present two experiments.

In our previous study (Eaves et al., 2012) participants saw a picture from a set of eight everyday rhythmical actions ("instructed action"). They then passively observed a short rhythmical distractor movie of either the same or a different action, before executing the instructed rhythmical action. Our subtle manipulation of distractor cycle times (slow or fast) produced a robust imitation bias in the cycle times of the participants' subsequently executed actions, that is, towards the speed of the observed distractor. This bias was only a small fraction both of our modulations in the distractor speed, and of the modulations that participants could produce when intentionally imitating the distractor speeds. Relative to a fully compatible condition, the imitation bias was reduced equally (but still present) in three incompatible conditions, wherein instructed and distractor actions differed in (a) type (e.g., tooth brushing vs. window wiping), (b) plane of motion (horizontal vs. vertical), or (c) both. Accordingly, we found no evidence for separable (i.e., additive) contributions when both action type and plane were simultaneously incompatible. Instead, the distractor's impact on motor processing was generally reduced whenever the observed action was not directly relevant to the observer's intended actions. We conceptualized this finding further using Cisek and Kalaska's (2010) framework of biased competition, and speculated that both the instructed and distractor actions can be modeled as parallel sensorimotor streams, which may or may not compete with one another.

In the present two studies, we employed the same extended (offline) SRC paradigm as in Eaves et al. (2012) and investigated the impact of different forms of MI during AO on this AI effect. The rationale for doing this was twofold. First, in our earlier study the compatibility between observed and executed actions had served to indirectly manipulate the competition between the two hypothetical sensorimotor streams. In the present studies, however, we used different MI instructions during AO (i.e., "AO + MI") as more direct means of manipulation. Second, a series of recent studies have shown the neurophysiological impact of instructing MI during AO. When participants imagined performing the action that they simultaneously observed (i.e., AO + MI), a larger number of corticomotor regions were activated compared to AO (Macuga and Frey, 2012; Nedelko et al., 2012; Berends et al., 2013; Villiger et al., 2013). Stronger activations in motor and motor-related areas were also shown for AO + imitative execution, compared to both AO + MI and AO alone (Macuga and Frey, 2012; Villiger et al., 2013). While those authors suggested motor rehabilitation and training programs might be enhanced if practitioners combined AO + MI instructions, to our knowledge there is currently no behavioral evidence to demonstrate the effects of such instructions on overt motor behavior.

In Experiment 1 we contrasted two types of AO + MI instructions. During distractor AO, participants imagined from a first person perspective the physical sensation and effort involved in performing the instructed action in synchrony with the rhythmical distractor (AO + synchronized MI), or they imagined their own hand in the static start-posture needed for the instructed action (AO + static MI). By definition synchronized MI instructed tight temporal couplings between the parallel AO and MI simulations, while static MI required participants to effectively decouple their internal simulation of their own rigid hand posture from the on-going and dynamic AO sensorimotor stream.

In Experiment 1 our first aim (1.1) was to investigate if the imitation bias was stronger in later execution for synchronized MI compared to static MI. Our second aim (1.2) was to investigate if synchronized MI would significantly enhance the imitation bias relative to that which we obtained previously for passive AO (Eaves et al., 2012). Our third aim (1.3) was to assess if static MI would reduce the bias relative to this same passive AO condition. In Experiment 2 we pursued four additional aims. Our first aim (2.1) was to assess whether overtly executing an action and synchronizing this with the distractor action (AO + synchronized execution) would increase the imitation bias relative to AO + synchronized MI. In addition, we explored whether the imitation bias would be specific to later execution of the action that was synchronized with the distractor (i.e., the "distractor-synchronized action"), or if synchronization would also influence later execution of (aim 2.2) different action types, and (aim 2.3) in different planes of motion. Finally, our fourth aim (2.4) was to replicate the findings obtained for synchronized MI in Experiment 1. We report Experiment 1 first, and then describe the rationales for the aims of Experiment 2 in more detail. In summary, we pursued the following aims:

Experiment 1

Is the imitation bias more pronounced for:

1.1. AO + synchronized MI compared to AO + static MI?
1.2. AO + synchronized MI compared to the imitation bias that we obtained previously for passive AO (Eaves et al., 2012)?
1.3. Passive AO compared to static AO?

Experiment 2

Is the imitation bias:

2.1. increased for AO + synchronized execution, compared to AO + synchronized MI?
2.2. reduced when, during AO, participants imagined (or executed) an action different from the subsequently executed action, compared to imagining (or executing) the same action?
2.3. reduced when, during AO, participants imagined (or executed) the instructed action in a plane different from that of the subsequently executed action, compared to imagining (or executing) in the same plane?
2.4. In addition, we were seeking to replicate the findings for synchronized MI in Experiment 1, namely that there was no effect of action type compatibility (aim 2.4a), and that synchronized MI produced a stronger imitation bias than static MI (aim 2.4b).

EXPERIMENT 1

TASK AND DESIGN

On each trial participants observed a picture of a to-be-pantomimed rhythmical action ("instructed action"), followed by a short distractor movie. They then executed the instructed action. We studied actions that are typically performed relatively slow ("habitually slow actions") as well as habitually fast actions. Within each habitual speed category, slow and fast versions of each distractor action were used.

Four blocks of thirty-two trials were conducted, with two blocks run on each consecutive day. A four-factorial repeated-measures design was used. MI content during distractor AO was manipulated across the two blocks run in each session (synchronized MI or static MI), in a counterbalanced order across participants. The other three factors were manipulated within each block of trials: habitual action speed (slow or fast), distractor speed (slow or fast), the compatibility between instructed and distractor actions, in terms of action type compatibility (same or different action: SA or DA), and dominant plane of motion compatibility (same or different plane: SP or DP). Combining the two individual compatibility manipulations yielded one compatibility factor with four levels: SA/SP, SA/DP, DA/SP, and DA/DP.

Note that the two factors of action type compatibility and plane compatibility were derived from pooling the data from their four constituent factors, namely: (1) instructed action type (face- or surface-oriented, see Materials and Methods), (2) instructed action plane (horizontal or vertical), (3) distractor action type (same or different), and (4) distractor action plane (same or different). The full combination of these four factors with habitual action speed and distractor speed resulted in 64 trials for both MI conditions, half of which were presented in a quasi-random order within each block on Day 1, and the other half on Day 2. As a result of the pooling, each cell of the effective four-factorial design consisted of an average across four trials.

We avoided two potential confounds that would have been associated with including a passive AO instruction in the present design. First, instructing both "passively observe" and "synchronize with" the distractor on consecutive and counterbalanced blocks in the same experiment could have encouraged active synchronization during passive AO trials. Second, an order effect would likely have been induced if all passive AO trials had been run at the start of each experiment. Therefore, we compared the data sets obtained from the present Experiments 1 and 2 to a passive AO data set that we collected previously (Eaves et al., 2012). While all three studies employed different instructions during AO, the cross-experiment comparison was equitable since all three experiments used the exact same trial structure and presented the same stimuli across trials for the same time periods. For a full description of all statistical analyses used, please see "Data Analysis."

RESULTS

The two-factorial ANOVA on the cycle time (ms) data yielded a significant main effect of distractor speed, $F(1,11) = 20.32$, $p = 0.001$, $\eta_p^2 = 0.65$. As predicted, response cycle times were shorter after seeing a fast compared to a slow distractor (608 vs. 668 ms; see **Figure 1**). Trivially, the main effect of habitual speed was also significant, $F(1,11) = 64.1$, $p < 0.001$, $\eta_p^2 = 0.85$. The two-way interaction between distractor speed and habitual speed was not significant.

The three-factorial ANOVA performed on the ratio data yielded only a significant main effect of MI content, $F(1,11) = 16.67$, $p < 0.01$, $\eta_p^2 = 0.6$ (see **Figure 2**). That is, the slow:fast ratio of response cycle times was significantly closer to that of the display (150%) following AO + synchronized MI (123%), compared to AO + static MI (102%). Both the main effects of compatibility and of habitual speed were not significant, and there were no significant interactions.

Running a series of simple effect analyses on the cycle time (ms) data for the synchronized MI condition confirmed that the main effect of distractor speed was significant in all four compatibility conditions (all ps ≤ 0.001, all η_p^2s ≥ 0.62). In contrast, for the static MI condition, the main effect of distractor speed was not significant in each of the three incompatible conditions (all ps > 0.41, all η_p^2s ≤ 0.06), and only approached significance for the fully-compatible SA/SP condition ($p = 0.076$, $\eta_p^2 = 0.26$).

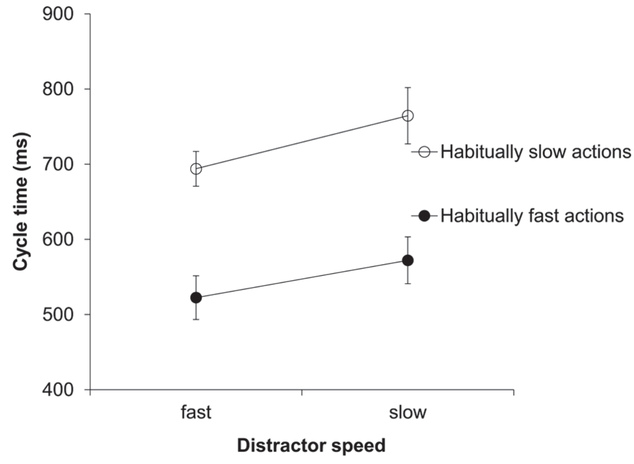

FIGURE 1 | Experiment 1: cycle times (ms). Mean cycle times for the factors habitual speed and distractor speed. Error bars show the standard error of the mean.

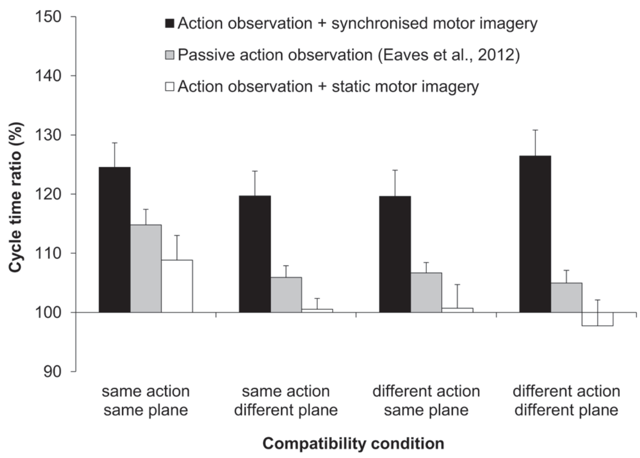

FIGURE 2 | Experiment 1: cycle time ratios (%). Mean cycle time ratios (with standard error of the mean) for three factors involved in Experiment 1: MI content, action type compatibility, and plane compatibility. Data obtained previously by Eaves et al. (2012) for passive-AO is also displayed. The cycle time ratio in the distractor actions was 150%.

Next we compared the imitation bias that we had obtained previously for passive AO (Eaves et al., 2012), to the bias obtained first for synchronized MI and second, for static MI. In both two-factorial, mixed measures ANOVAs the between-subjects factor was experiment (two levels) and the within-subjects factor was compatibility (three levels: SA/DP, DA/SP, and DA/DP). Note that the fully compatible SA/SP condition was excluded from both of these analyses. Since we previously submitted that participants could have covertly used the fully compatible "task-irrelevant" distractor as a strategic guide for their own actions, only the incompatible conditions in our previous experiment can be taken as evidence for genuine AI effects. The first of these two analyses compared passive AO to synchronized MI (see **Figure 2**). The main effect of experiment was significant, $F(1,20) = 12.02$, $p < 0.01$, $\eta_p^2 = 0.38$. Here the magnitude of the imitation bias was significantly stronger for the present synchronized MI condition (122%) compared to that for passive AO (106%). The main effect of compatibility and the two-way interaction between experiment and compatibility was not significant. The second of these two analyses compared passive AO to static MI. Here the main effect of experiment exhibited only a trend towards significance, $F(1,20) = 2.86$, $p = 0.110$, $\eta_p^2 = 0.13$, wherein the imitation bias was numerically reduced for static MI relative to passive AO (100 vs. 106%). The main effect of compatibility and the two-way interaction between experiment and compatibility was not significant.

DISCUSSION

Regarding our first aim (1.1), synchronized MI significantly enhanced the magnitude of the imitation bias across all four compatibility conditions compared to static MI (123 vs. 102%, respectively). With regard to our second aim (1.2), the imitation bias was significantly more pronounced for the three incompatible synchronized MI conditions compared to the three incompatible passive AO conditions that we had previously studied (123 vs. 106%, Eaves et al., 2012). The most likely explanation is that synchronized MI increased the strength of sensorimotor coupling to the display. In essence, for synchronized MI we instructed participants to generate a dynamic internal motor simulation of the instructed action. This involved imagining the physical sensation and effort involved in performing this action. They then coupled the spatio-temporal features of this internal simulation with those of the second sensorimotor representation – that of the observed distractor action. Accordingly, this instruction enhanced (covert) sensorimotor coupling with the display, which biased later execution.

We further found that the imitation bias was equally strong across the four compatibility conditions for AO + synchronized MI. This indicates that similarly tight temporal couplings are possible between AO and MI, even when their contents do not match, with respect to the action type, plane of motion, or both. Accordingly, AO + synchronized MI appears to be a relatively flexible process that can accommodate a good range of AO + MI configurations.

These findings have direct importance for applied practitioners who wish to improve motor learning (e.g., in sports, pilates, yoga, and dance) and rehabilitation procedures (e.g., in stroke and neuro-degenerative patients). Practitioners typically regard both AO and MI as two potentially useful but distinctly separate adjunct tools (see Hodges et al., 2007; Braun et al., 2013; Poliakoff, 2013). However, our data provide the first behavioral evidence that combined AO + MI instructions can significantly modulate AI effects in the kinematics of later execution. Therefore, the present findings are in line with the recommendations of the recent neurophysiological studies (Macuga and Frey, 2012; Nedelko et al., 2012; Berends et al., 2013; Villiger et al., 2013), in that they support calls for new approaches to rehabilitation and training to include combined AO + MI instructions (see Vogt et al., 2013).

Regarding our third aim (1.3) we found that the imitation bias, which was clearly present following AO + synchronized MI, was largely absent after AO + static MI. For static MI there was no significant main effect of distractor speed in any of the four compatibility conditions (the numerically larger bias for the compatible distractors presumably indicates that it was slightly harder to remain decoupled from the display when the observed and imagined actions matched). In addition, we found a clear trend for a reduced imitation bias in static MI (100%) relative to passive AO (106%) in Eaves et al. (2012), where distractor speed effects were significant in each individual compatibility condition. Most likely, the absent imitation bias for the static MI condition is due to a dominant effect of MI (here: static) on subsequent motor execution, relative to the otherwise robust effect of AO. This result was not unexpected, given that participants were instructed to decouple their MI content from the concurrent AO process in the static MI condition.

Taken together the present data provide a first clear-cut demonstration of the strong modulatory effects of MI instructions during AO. While synchronized MI enhanced the imitation bias beyond passive AO, even under conditions where AO and MI contents were not identical, static MI practically abolished this AI effect. Our data also provide the first empirical support for a spectrum of different AO + MI states, ranging from congruent to coordinative, and finally to conflicting cases of AO + MI, as described next (for an extended account, see Vogt et al., 2013).

First, as in our Experiment 1, the neurophysiological experiments described in the Introduction used *congruent AO + MI* instructions: participants imagined themselves performing the same action that they simultaneously observed (c.f., Nedelko et al., 2012; Macuga and Frey, 2012). In our version of this task, we instructed participants to "switch on" their awareness of their own body schema and map the observed action onto their own felt hand (i.e., compatible synchronized MI). Subjectively this is different from simply observing, and our behavioral data clearly underpin this. A second AO + MI state is *coordinative AO + MI,* which was represented in the present design by the incompatible synchronized MI conditions. In contrast to congruent AO + MI, which directs a narrow focus of attention towards tight synchronization, coordinative AO + MI offers a potentially limitless array of spatio-temporal configurations between observed and imagined actions. Therefore, this arrangement invites many open questions and interesting lines of empirical enquiry (see Vogt et al., 2013). In rehabilitation, for example, patients might benefit from watching video-taped repetitions of a naturalistic action while making progressive changes in either range of motion or force production in their coordinated MI across trials. Most likely, both congruent and coordinative AO + MI states can be shaped into effective training procedures.

Finally, congruent and coordinative AO + MI states can be distinguished from cases of *conflicting AO + MI*, which we have implemented here via the static MI condition. While such conditions are unlikely beneficial for practitioners, they may prove an important research tool, similar to the use of compatible and incompatible visual stimuli in research on AI. It is also useful to contrast the present detrimental effect of static MI on AI with other proposed inhibitory mechanisms. In particular, previous research has identified that both AO and MI can give rise to motor commands, but that these are typically blocked at some level of the motor system by inhibitory mechanisms (e.g., Hardwick et al., 2012; and see Brass and Heyes, 2005; Guillot et al., 2012). At present, the processes by which this inhibition is achieved are not yet clear. For example, it is not clear whether inhibition is mediated by specific brain structures, or by intracortical facilitation/inhibition (Di Rienzo et al., 2013). In contrast, the present detrimental effects of static MI on AI most likely reflect a different class of "inhibitory" processing, namely a decoupling of the default impact of AO on motor processing by concurrent engagement in conflicting MI. For example, in an applied sporting context, MI of an action that differs from that of an observed opponent is one feasible strategy for avoiding an unwanted bias in later execution. Although this is presently a tentative suggestion, it may warrant further empirical investigation in the future.

Overall, Experiment 1 shows: (1) combined AO + MI instructions can enhance AI effects relative to passive AO; (2) AO and MI content can be flexibly coordinated across different planes and different action types; and (3) conflicting AO + MI content can abolish AI effects. Furthermore, we hope that the above classification of the three AO + MI states might motivate both applied and basic researchers to examine the boundaries, characteristics and opportunities for practical implementation of each state further. In Experiment 2 we explored two related themes. First, we studied the potentially stronger impact of motor execution, as compared to MI, during AO. Second, we manipulated the overlap between MI (and motor execution) content during AO with the subsequently executed action, in order to further explore the specificity of the imitation bias.

EXPERIMENT 2

Since the largest gains in motor proficiency are most likely available through physical rather than mental practice (c.f., Higuchi et al., 2012), we wanted to assess the relative contributions of each. Therefore, in Experiment 2 our first aim (2.1) was to compare the magnitude of the imitation bias for AO + synchronized MI relative to that obtained from synchronizing overt motor execution with the display (AO + synchronized execution). For two reasons we expected an increase in the imitation bias for synchronized execution compared to synchronized MI. First, sensorimotor involvement should increase during synchronized execution (e.g., Macuga and Frey, 2012; Villiger et al., 2013). Second, temporary losses in synchronicity may be more frequent for synchronized MI, where afferent information is reduced. Given that there was no compatibility effect for synchronized MI in Experiment 1, we expected similar results for synchronized execution in Experiment 2.

In Experiment 2 we also studied the effects of a wider range of MI and overt synchronization instructions on subsequent execution. While in Experiment 1 the content of MI was always the to-be-executed (instructed) action, in Experiment 2 we used three different "synchronization type" instructions (i.e., for both MI and overt execution during AO, see aim 2.1). The first condition, "Synchronize the Instructed action" (SI), resembled the standard instructions in Experiment 1. Relative to this SI condition, we manipulated the extent of the overlap between the imagined (or overtly executed) action with the observed action in two ways. In the second condition, "Synchronize the Distractor action" (SD), participants imagined performing (or overtly performed) the action shown in the distractor movie. Independent of this manipulation, we again manipulated the compatibility between the instructed and distractor actions (manipulation of "action type compatibility" as in Experiment 1). This meant that, during observation of incompatible distractor actions, participants imagined (or executed) an action that was the same as the distractor, but different from the instructed action that they would later execute (e.g., while observing window wiping they imagined performing window wiping and then subsequently executed tooth brushing). Note that for compatible action types, the SI and SD conditions were identical.

The third synchronization instruction in Experiment 2 was "Synchronize the Instructed action in the Orthogonal Plane" (SIOP). Here participants imagined performing (or overtly performed) the instructed action but in the plane orthogonal to that shown in the distractor movie. Note that, unlike in Experiment 1, in Experiment 2 the dominant plane of motion was always compatible between the instructed and distractor actions, thus the plane of the synchronized action was always different from that of both the instructed and distractor actions. For a full overview of the experimental conditions in Experiment 2, see **Figure 4** and **Table 1**.

The purpose of the SD and SIOP conditions was to assess if reducing the overlap between the distractor-synchronized action and the subsequently executed action would affect the imitation bias towards the observed rhythm, relative to the standard SI condition. Specifically, in the incompatible SD condition, we were interested if imagining (or performing) a given action with a certain distractor speed would also affect the speed of subsequently performing a different action (aim 2.2). A negative finding would demonstrate a highly action-specific priming effect, whereas a positive finding would demonstrate a degree of generalization for the observed rhythm across different imagined and executed actions.

Regarding our third aim (2.3) we assessed if imagining (or performing) a given action with a certain distractor speed would also affect the speed of subsequent execution in a different plane (i.e., compatible SIOP vs. compatible SI trials). A negative finding would indicate that the imitation bias was highly plane-specific, whereas a positive finding would demonstrate a degree of generalization of the imagined (or performed) rhythm across different planes of motion. Note that the manipulation of plane compatibility in our previous studies (Eaves et al., 2012, and Experiment 1 in the present paper) does not inform on this issue, since the previously imagined and to-be-performed planes of motion had always been identical. In addition to the two main aims regarding the manipulations of synchronization type (i.e., aims 2.2 and 2.3) we also studied if the possible plane-specific imitation effect might be further affected by a discrepancy between the observed and imagined (or performed) action. For example, it is conceivable that imagining vertical toothbrushing while observing horizontal tooth brushing affects the rhythm of subsequently performed horizontal toothbrushing (action-compatible

Table 1 | Summary of the three synchronization instructions in Experiment 2.

Synchronization type	Instructed action (picture)	Distractor action (movie)	Action synchronized with distractor	Executed action
Synchronize Instructed action (SI)	Tooth brushing	Window wiping	Tooth brushing	Tooth brushing
Synchronize Distractor action (SD)	Tooth brushing	Window wiping	Window wiping	Tooth brushing
Synchronize Instructed action in the Orthogonal Plane (SIOP)	Tooth brushing	Window wiping	Orthogonal tooth brushing	Tooth brushing

These instructions varied the degree of overlap between the action that was synchronized with the distractor and the subsequently executed instructed action. Within each synchronization type, participants were instructed to either imagine or overtly perform the required action during distractor observation. The table shows the instructions for one example trial involving incompatible actions.

SIOP condition), but also that the imitation bias might be weaker still when the MI needs to be synchronized with a movie of horizontal window wiping (action-incompatible SIOP condition, see **Table 1**).

Our fourth aim (2.4) for Experiment 2 was to replicate, via the SI condition, two findings from Experiment 1. Namely, can synchronized MI: (aim 2.4a) remove the action type compatibility effect as found in Eaves et al. (2012); and (aim 2.4b) enhance the imitation bias relative to both static MI and to our previous passive AO effects. Contrary to the SI condition, we predicted that action type compatibility would modulate the imitation bias in both the SD and the SIOP conditions. Therefore, we should also find a two-way interaction between synchronization type and action type compatibility. Within each synchronization type, we expected this finding to be pronounced similarly within each synchronization mode.

TASK AND DESIGN

The same basic trial structure was used as in Experiment 1, whereby participants saw on each trial a picture of the instructed action, then a rhythmical distractor movie, and then executed the instructed rhythmical action. Unlike in Experiment 1, we kept the dominant plane of motion compatible between the instructed and distractor stimuli. Six blocks of thirty-two trials were conducted, with three blocks run on each of the two consecutive days. A five-factorial repeated-measures design was used. Across the three blocks run on each day participants followed one of three synchronization type instructions. First, as in Experiment 1, during distractor observation participants performed the instructed action type and synchronized this with the movie, before executing the instructed action (Synchronize Instructed action: SI). Second, in condition "Synchronize Distractor action" (SD) we instructed participants to perform the distractor action type and synchronize this with the movie before executing the instructed action type. Third, in condition "Synchronize Instructed action in the Orthogonal Plane" (SIOP) participants performed the instructed action type and synchronized this with the movie, but in the orthogonal plane to that of the distractor movie. For a summary of these conditions, please see **Table 1**.

Each of the three larger blocks described above were split into four mini-blocks of eight trials. Synchronization mode (synchronized MI or synchronized execution, see aim 2.1 above) was manipulated across consecutive mini-blocks in an alternating order, which was counterbalanced across participants. The other three factors were manipulated within each mini-block of trials: habitual action speed (slow or fast), action type compatibility between the instructed and distractor actions (same action or different action; SA or DA), and distractor speed (slow or fast).

As in Experiment 1, we pooled the data across the constituent factors, resulting in 64 trials for each of the three synchronization types, half of which were presented in a quasi-random order across the four mini-blocks in session one, and the other half in session two. Again, each cell of the effective five-factorial design consisted of an average across four trials.

RESULTS

The two-factorial ANOVA on the cycle time (ms) data yielded a significant main effect of distractor speed, $F(1,13) = 41.46$, $p < 0.001$, $\eta_p^2 = 0.76$. As predicted, response cycle times were shorter after seeing a fast compared to a slow distractor (614 vs. 710 ms; see **Figure 3**). Trivially, the main effect of habitual speed was also significant, $F(1,13) = 119.23$, $p < 0.001$, $\eta_p^2 = 0.9$. The interaction between distractor speed and habitual speed was also significant, $F(1,13) = 10.36$, $p < 0.01$, $\eta_p^2 = 0.44$. This reflected the fact that, although the ratio of slow:fast distractor speeds was the same for each habitual speed (150%), the absolute difference between distractor cycle times was greater in habitually slow actions compared to habitually fast actions (see Data Analysis).

The four-factorial ANOVA on the cycle time ratio (%) data yielded a significant main effect of synchronization mode, $F(1,13) = 12.38$, $p < 0.01$, $\eta_p^2 = 0.49$ (see **Figure 4**). Overall, the imitation bias was more pronounced for synchronized execution compared to synchronized MI (119 vs. 115%, respectively). The main effect of synchronization type was also significant, $F(2,23) = 3.4$, $p = 0.05$, $\eta_p^2 = 0.21$. Pairwise comparisons identified that the imitation bias was more pronounced for the SI condition compared to the SIOP condition (119 vs. 115%; $p = 0.01$), while these two conditions were not significantly different from the SD condition (117%; both ps > 0.05). The main effect of action type compatibility was significant, $F(1,13) = 27.08$, $p < 0.001$, $\eta_p^2 = 0.68$, wherein the response cycle time ratio was closer to the display ratio (150%) for compatible compared to incompatible action types (119 vs. 115 %). Different from the ANOVA on

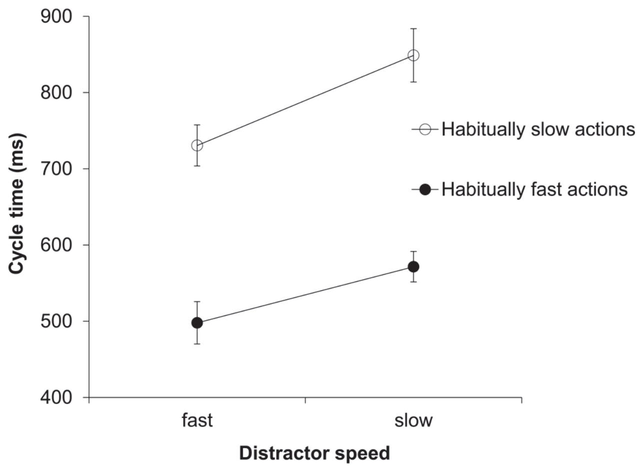

FIGURE 3 | Experiment 2: cycle times (ms). Mean cycle times for the factors habitual speed and distractor speed. Error bars show the standard error of the mean.

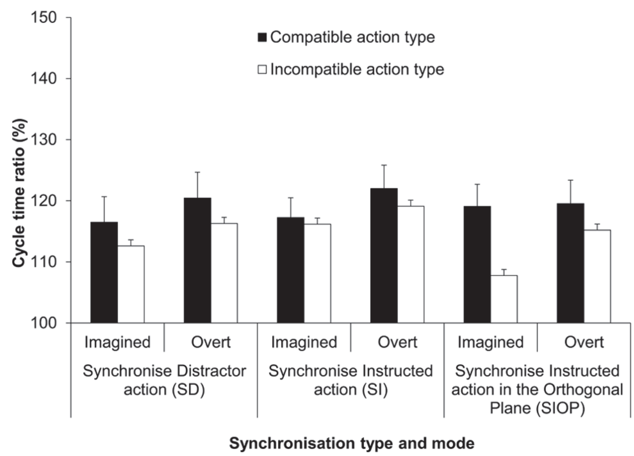

FIGURE 4 | Experiment 2: cycle time ratios (%). Mean cycle time ratios (with standard error of the mean) for the factors synchronization type, synchronization mode and action type compatibility. The SI condition (also used in Experiment 1) served as a reference condition for both the SD and SIOP conditions. The cycle time ratio in the distractor actions was 150%.

the mean cycle time data (ms), the effect of habitual speed was not significant in the cycle time ratios, confirming that the imitation bias was pronounced similarly for both habitual speeds, when expressed as cycle time ratios.

The only significant interaction was between synchronization type and action type compatibility, $F(1.36,17.69) = 4.7$, $p = 0.03$, $\eta_p^2 = 0.27$. Pairwise comparisons showed that the imitation bias was significantly reduced when action type was incompatible compared to compatible between the instructed and synchronized action for both the SD (119 vs. 115%; $p < 0.03$) and the SIOP conditions (119 vs. 112%; $p < 0.001$), but not for the SI condition (120 vs. 118%; $p > 0.05$). A series of more specific simple main effect analyses compared compatible vs. incompatible action type within each synchronization mode for both the SD and SIOP conditions. These analyses confirmed that the bias was significantly reduced for incompatible compared to compatible trials within both modes for both the SD and SIOP conditions (all *p*s < 0.05). Additionally, when action type was compatible within both synchronization modes the bias was not modulated across the SI, SD, and SIOP conditions. First, these results confirm that in the SD condition the bias was reduced when the action type differed between the instructed and synchronized action for both synchronization modes. Second, in the SIOP condition the bias was not reduced when only plane was incompatible between these two actions. However, the bias was reduced when orthogonal synchronization was with an incompatible compared to a compatible action type within both synchronization modes (see **Figure 4**).

In two further analyses we compared the SI condition from Experiment 2 to the two MI conditions in Experiment 1. Both simple main effect analyses involved one between-subjects factor of experiment (two levels) and one within-subjects factor of action type compatibility (SA/SP or DA/SP). The latter reflected the fact that although four compatibility levels were used in both of our previous experiments, action type was the only compatibility factor manipulated in Experiment 2. The first analysis compared the present synchronized MI data (SI condition) to the equivalent synchronized MI data from Experiment 1. The main effects of experiment and of action type compatibility, as well as the related two-way interaction, were not significant. Therefore the magnitude of the bias for synchronized MI was replicated across Experiments 1 and 2. The second analysis compared the synchronized MI data from Experiment 2 (SI condition) to the static MI data from Experiment 1. The main effect of experiment was significant, $F(1,24) = 9.5$, $p < 0.01$, $\eta_p^2 = 0.28$, wherein the imitation bias was greater for the present synchronized MI condition (117 vs. 105%, respectively). Again this replicated our earlier finding from Experiment 1. Unexpectedly, the main effect of action type compatibility was significant, $F(1,24) = 5.11$, $p = 0.03$, $\eta_p^2 = 0.18$, wherein the bias was more pronounced for compatible compared to incompatible trials (113 vs. 108%), indicating a pocket of stronger distractor effects in a subset of the data. The two-way interaction between experiment and action type compatibility was not significant.

In two final steps we ran further simple main effect analyses. First, running these analyses on the cycle time (ms) data confirmed a significant main effect of distractor speed within each of the 12 conditions in Experiment 2 (all *p*s < 0.027, all η_p^2s ≥ 0.32). Second, we then compared each of these twelve conditions to the fully-incompatible, and therefore most conservative, passive AO condition from our previous study (i.e., DA/DP, Eaves et al., 2012). The imitation bias for ten of the twelve conditions in Experiment 2 was significantly greater than that for passive AO (all *p*s ≤ 0.03). However, the bias was not significantly greater than passive AO for synchronized MI when action type was incompatible between the instructed and synchronized actions in both the SD and the SIOP condition.

DISCUSSION

Regarding our first aim (2.1), the significant main effect of synchronization mode showed that the imitation bias was enhanced following overt compared to imagined distractor synchronization.

This result was largely anticipated, since Macuga and Frey (2012) and Villiger et al. (2013) have already demonstrated stronger activations for AO + execution in a number of cortical sites. Here we provide the first behavioral evidence that nicely corresponds to this. It is most likely that the imitation bias was enhanced by increases in somatosensory feedback during overt compared to imagined execution. Accordingly, we can speculate that temporal losses in synchronicity are more common for AO + MI compared to AO + execution. This is interesting since a tight temporal coupling is typically found between an observed action and its internal motor representation (e.g., Borroni et al., 2005; see also Rizzolatti and Sinigaglia, 2010). Evidence from mental chronometry research has also established the principle of temporal congruency, whereby both MI and execution of the same action typically follow the same time course (see Collet et al., 2013). As such, more detailed studies are now required to examine the degree of spatio-temporal coupling between parallel internal simulations for different AO + MI configurations. Overall, the findings from the present two studies indicate that combined AO + MI instructions will be most useful in applied settings when overt execution is either restricted or not possible, for example, due to time or injury constraints. However, further research is needed to establish the efficacy of more specific instructions for practitioners.

Research using event-file paradigms has shown that when certain perception-action features co-occur during action observation (here: action type and rhythm), the neural signatures representing those particular features become closely associated (e.g., Nattkemper et al., 2010; Kühn et al., 2011). In our case, the execution or imagery of a given action should bias its subsequent execution towards the rhythm associated with it, whilst execution of an action without such association would not carry the same bias. Indeed we found that the imitation bias was present in all twelve compatibility conditions in Experiment 2. However, in relation to our second aim (2.2), both the main effect of action type compatibility and the two-way interaction between synchronization type and action type compatibility were significant. Simple main effect analyses showed that the imitation bias was significantly reduced for both execution modes in the SD condition when the instructed action type was incompatible compared to compatible with the distractor-synchronized action. Therefore, synchronization does not bias the execution of all subsequent actions to the same degree. Instead, our results highlight a degree of specificity for synchronization effects, whereby later execution is more strongly biased for action types that are represented during and, therefore, are directly involved in distractor synchronization. The absence of a compatibility effect within both modes for the SI condition is in line with this argument, since the instructed action was always represented during distractor synchronization in the SI condition. Here we replicate the result found for synchronized MI in Experiment 1 (see aim 2.4a), and show that the same trend exists for overt motor synchronization. Overall, although both imagined and overt actions can be flexibly coordinated with a range of observed actions that differ in planes and action types, this synchronization did not bias motor execution of a similarly broad range of action types. This was markedly so for the incompatible synchronized MI trials in the SD condition, where the imitation bias was no greater than that for our previously obtained passive AO condition (Eaves et al., 2012).

Regarding our third aim (2.3), simple main effect analyses showed that synchronizing with the distractor in the opposite plane alone (i.e., compatible SIOP trials) did not affect the imitation bias relative to the standard SI condition. This result complements our earlier finding for the plane compatibility manipulation in Experiment 1 (for AO + synchronized MI). Together these results demonstrate that AO and MI contents can be flexibly coordinated across different planes of motion and, accordingly, that the AI effect as studied here does not rely on plane compatibility. Previous research has shown that when an actor performs a rhythmical arm movement while observing a spatially orthogonal rhythmical action, variability increases in the actor's movements orthogonal to the instructed action (Kilner et al., 2003, 2007; Bouquet et al., 2007; Richardson et al., 2009; Romero et al., 2012). Accordingly, it is possible that a similar interference effect occurred during AO + synchronization in the present SIOP trials. However, the present design was not optimized to study such effects, and we instead used the cycle time of later execution to indicate the temporal coordination between the previously observed and synchronized actions. Here we demonstrate that, despite those possible increases in spatial variability, plane compatibility did not modulate the temporal coupling for both overt and imagined actions. This tentatively suggests that temporal couplings are relatively unaffected by spatial alignment.

While the compatible SIOP condition did not modulate the imitation bias relative to the compatible SI condition, we did find that the bias was reduced, although still present, for incompatible compared to compatible SIOP trials in both execution modes, that is, when participants synchronized in a different plane with a different distractor action. This result is in line with that for the incompatible vs. compatible SD trials. The action-incompatible SIOP trials thus identified a further boundary condition to the otherwise rather flexible coordination of AO and MI contents. This is not too surprising, given that this condition presented a considerable challenge to participants, in terms of the complexity of the task. This was primarily born out when synchronization was imagined rather than overt, which presumably reflected a reduced motor involvement for MI compared to execution. Overall, while the imitation bias was present in each of the 12 compatibility conditions of Experiment 2, the reduced bias found for the action-incompatible SD and SIOP conditions identifies a degree of specificity of AO + MI processes for the subsequently performed action.

With regard to our fourth aim (2.4b), Experiment 2 nicely replicated our finding from Experiment 1 that the imitation bias for synchronized MI was greater than that for both static MI (Experiment 1) and passive AO (Eaves et al., 2012). The imitation bias was also pronounced equally across Experiments 1 and 2. However, unlike in our previous analysis of synchronized MI vs. static MI in Experiment 1, which involved four compatibility levels, there was a main effect of compatibility when synchronized MI (Experiment 2) was compared to static MI (Experiment 1). Here the bias was stronger for compatible trials when only the SA/SP and DA/SP conditions were compared across the two experiments. This was likely due to the numerically greater distractor effects for compatible static MI (see **Figure 2**). However, in the main three-factorial ANOVA in Experiment 1 there was no main effect of compatibility or significant interaction involving compatibility and MI content, and since the simple main effect analyses in Experiment 1 revealed that static MI reduced the distractor effects in each compatibility condition (ms data), we refrain from further interpretation of this small pocket of significant findings in a subset of the data.

GENERAL DISCUSSION

Foremost in the present data is that combined AO + MI instructions can facilitate AI effects in the cycle times of subsequently executed rhythmical actions. Therefore, our behavioral data support the calls for applied practitioners to include combined AO + MI instructions in motor training and rehabilitation programs. We also show that AO and MI content can be flexibly coordinated across different action types and different planes, and this can bias actions executed in either the same or orthogonal plane equally. We additionally show that static MI can practically abolish AI effects in later execution.

While integrative accounts of AO and MI as sub-forms of action simulation are not new (see Shepard, 1984; Jeannerod, 1994, 2001, 2006), research efforts to study their contributions to action execution have largely branched out to focus on *either* AO *or* MI (see Vogt et al., 2013). Our paradigm represents a return to a more integrated approach to investigating these two closely related processes. As such, the data we obtained in Experiment 1 led us to distinguish three AO + MI states, ranging from congruent over coordinative to conflicting AO + MI states (Vogt et al., 2013). We hope these distinctions pave the way for both practitioners and experimental researchers to examine the boundaries, characteristics, and applied opportunities of each state further. Next we outline some considerations for future research in this area.

First, since congruent AO + MI instructions enhanced motor execution relative to passive AO, a major concern is that this strategy has seldom been accounted for in many of the existing AO experiments. In a large number of neuroimaging studies on AO, participants could have either covertly or spontaneously re-interpreted standard AO instructions as an AO + MI instruction. For example, it is not completely clear whether AO + MI was undertaken even on some "pure" AO trials in the four aforementioned imaging studies. Since we clearly show that combined AO + MI instructions can bias motor execution more strongly than passive AO, future studies should address this potential confound, wherein imaging data (in conjunction with behavioral measures) will be useful for more careful contrasts between pure AO, pure MI, and AO + MI content. Second, while the imitation bias was enhanced equally by both congruent and coordinative AO + MI in the present studies, future research could investigate more closely under which conditions superior training conditions might be afforded by one or the other AO + MI state. Third, we observed that during conflicting AO + MI (static MI in Experiment 1), the imitation bias was practically abolished. While this instruction will unlikely be beneficial for practitioners in the field, it may prove useful as a methodological tool, similar to the use of compatible and incompatible stimuli in research on AI. For example, this approach could address whether an inverse effect for AO on MI exists, wherein the resilience of MI to conflicting AO conditions is presently unknown.

We also showed that synchronising motor execution with AO produced a stronger imitation bias compared to AO + synchronized MI. This finding is in line with those neurophysiological studies showing greater motor cortical activations for AO + execution compared to both AO + MI and AO (Macuga and Frey, 2012; Villiger et al., 2013). Our behavioral data indicate that those increased motor activations could reflect increases in sensorimotor coupling processes. Overall, since AO + synchronized execution enhanced the bias further, AO + MI instructions appear best suited to applied settings when motor execution is either restricted or not possible, that is, due to time or injury constraints.

Findings from event file paradigms (see Nattkemper et al., 2010) indicate that the co-occurrence of perception-action features would likely bias the execution of similar rhythmical actions. Indeed we found that the imitation bias was pronounced in all twelve compatibility conditions in Experiment 2. However, our findings for the incompatible SD and SIOP conditions highlight a degree of specificity for covert synchronization effects. Our data indicate that execution is biased more strongly by preceding sensorimotor processing when these two processes involve the same action. In comparison, disparity of plane between these two processes alone did not reduce the imitation bias. Therefore, although synchronizing motor processes (both MI and overt execution) with an observed action can accommodate a good range of configurations, we have also identified action disparity as a tentatively limiting factor.

Overall, Experiments 1 and 2 provide the first empirical evidence for the strong impact of different AO + MI states on AI effects in rhythmical actions. The distinction of the three AO + MI states now invites a range of new empirical and theoretical questions. For example, in which ways can we further assess the spatio-temporal couplings between parallel AO and MI streams, and what moderating roles might the sense of agency, MI perspective, and individual differences in motor expertise play? We believe the present work provides a valuable platform for addressing these issues further in an integrative way.

MATERIALS AND METHODS

EXPERIMENT 1

Participants

Twelve female participants (mean age 20.7 years; SD = 0.8 years) volunteered for the study. All had normal ($n = 10$) or corrected-to-normal vision. Participants were naïve to the study's purpose, right-hand dominant, and without physical injuries. Written informed consent was obtained prior to participation, and ethical approval was granted by Lancaster University.

Stimuli and apparatus

A conventional digital video camera (Panasonic NV-MX500B) was used to create the instructed action pictures and distractor movie stimuli. In total we used four different instructed actions. These were categorized either as actions that would typically be performed at a habitually slow pace (face washing: face-orientated;

painting: surface-orientated) or fast pace (tooth brushing: face-orientated; window wiping: surface-orientated). Since each action was also instructed to be in either the horizontal or vertical plane, this gave a total of eight different instructed action pictures (**Figure 5**). The model performed all actions with her left hand to provide mirror images of the participants' subsequent actions, who always executed actions with their right hand. This arrangement provided spatial compatibility between displayed and performed actions, which can facilitate imitation relative to an anatomically matched but spatially incompatible arrangement (e.g., Koski et al., 2003; Buccino et al., 2004).

Sixteen distractor movies were used in the main experiment, one slow and one fast version of each of the eight instructed actions. During filming, the model's performance had been paced by a metronome to achieve the exact distractor speeds shown in **Table 2**, whereas throughout the experiment all stimuli were displayed without sound. Importantly, instructed action stimuli were always paired with a distractor stimulus from within the same habitual speed category. We used two habitual speeds for two reasons: first, we wanted to assess the imitation bias of the distractor movies on motor execution across a range of cycle times and not just for one speed. Second, the fact that participants executed, in quasi-random order, rhythmical actions with two substantially different habitual speeds served to divert their attention away from the more subtle manipulation of the distractor speeds. Finally, note that each instructed action was displayed with the relevant object (sponge, paintbrush, toothbrush, or cloth), which enabled quick discrimination between the actions, whereas participants performed pantomimed actions (i.e., without objects). The latter was done to avoid participants having to select the relevant object in the beginning of each trial. The distractor movies showed pantomimed actions to allow participants to better distinguish between instructed and distractor stimuli, and to potentially strengthen the impact of the distractor stimuli on their subsequent pantomimed execution.

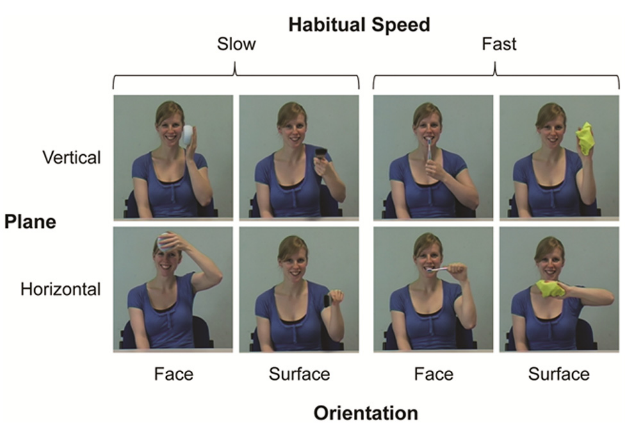

FIGURE 5 | Instructed action stimuli with the factors habitual speed, dominant plane of motion, and orientation (as used in Eaves et al., 2012).

Table 2 | Distractor stimuli specifications.

Parameters	Habitually slow actions		Habitually fast actions	
Distractor speed	**Slow**	**Fast**	**Slow**	**Fast**
Beats per min	60	90	120	180
Cycle times (ms)	1000	667	500	333
Total cycles in 4 s	4	6	8	12
Slow:fast ratio (%)	150		150	

Participants sat at a wooden desk in a dimly lit room facing a 17-in LCD computer monitor (Apple Studio Display) positioned approx. 80 cm away from their head. All stimuli were displayed against a light gray background via PsyScript 2.3 software (https://open.psych.lancs.ac.uk/software/PsyScript.html) running on a Power Macintosh G4 computer fitted with a digital I/O board. The start location for the participants' right index finger and thumb was on an electro-conductive plate mounted on top of a 23 cm-tall wooden post, 20 cm in front of them on the desk. A magnetic motion sensor was fitted to the distal end of the second metacarpal bone of the right hand. Participants' kinematic data were sampled at 103 Hz in 3-D space for 4 s periods using a Minibird Magnetic Tracking System (Ascension Technology Corp.), and stored on a separate PC. At the end of each trial, kinematic data plots were displayed on a second monitor, unseen by participants.

Procedures

Familiarization. In Phase 1 participants learned to pantomime each action from a set of eight familiarization movies (eight actions with two attempts each). These movies were identical to the movies in the main experiment, except that the cycle times were mid-way between the distractor speeds shown in **Table 2**, that is, 75 bpm for the habitually slow actions, and 150 bpm for the habitually fast actions. Participants were given verbal feedback about their movement based on the kinematic plots visible to the experimenter. This ensured that their movement amplitude and cycle time aligned closely with the medium-paced stimuli. In Phase 2, participants saw a picture of each action while simultaneously pantomiming the same action for 4 s (16 trials). In Phase 3, they experienced the structure of trials for the main experiment, including the four compatibility conditions (16 trials).

In Phase 4, participants repeated Phase 3 but performed MI during AO. During distractor AO, participants imagined from a first person perspective the physical sensation and effort involved in either (1) performing a dynamic version of the instructed action that was time-synchronized with the rhythmical distractor (AO + synchronized MI), or (2) adopting the static start-posture needed for the instructed action (AO + static MI). Compatible and incompatible MI content was practiced in both conditions, and overt movements were only executed after distractor offset. In Phases 2 to 4, verbal feedback was only given if movements occasionally drifted away from the criterion amplitude (10 cm for all actions) or cycle times. Short versions of this familiarization procedure were run on each new day of testing.

Main experiment. When participants placed their fingers in the start location, a green circle appeared on the monitor for 1 s to mark the beginning of a trial (Event A in **Figure 6**). (B) Then a picture of the to-be-pantomimed "instructed action" was shown for 1.5 s, followed by (C) a distractor movie of the same girl pantomiming either the same or a different action for 4 s. During distractor observation participants engaged in either synchronized MI or static MI, while visually fixating on the model's left eye, rather than directly coupling their vision to the model's rhythmical arm movements (c.f., Schmidt et al., 2007; Eaves et al., 2012). (D) For Experiment 2 only, a pause was inserted (red dot) to separate synchronized execution from (E) execution of the instructed action, which was cued by the appearance of a neutral, light-gray background. The end of the 4 s kinematic recording interval (E) was indicated by a computer-generated auditory signal, after which participants were sometimes asked to verbally report distractor characteristics (see below) before moving their hand back to the start location.

In both Experiments 1 and 2 the core manipulation across trials was that of distractor speed, with a ratio of slow:fast movements of 150% (see **Table 2**). Participants were not informed of the distractor speed changes, and this manipulation was further concealed by the more prominent differences between the two habitual speeds across trials. To focus their attention on the distractor movie, participants in both experiments were asked to verbally recall the distractor properties (action type and dominant plane of motion) at the end of approximately 10% of trials. In both experiments testing was distributed over two consecutive days to reduce the possibility of physical fatigue. All blocks of trials were preceded by a single warm-up trial and interspersed by short rest periods.

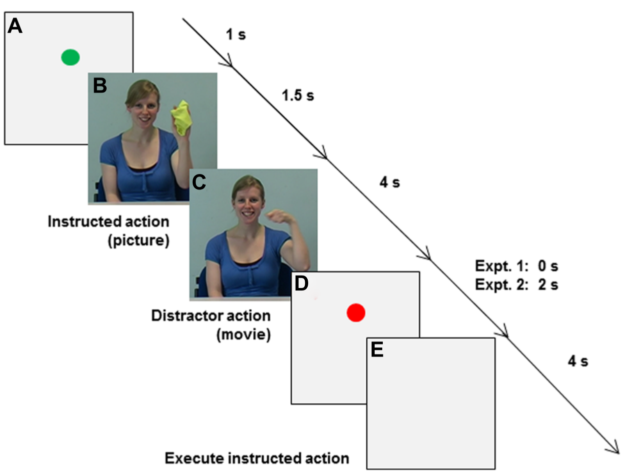

FIGURE 6 | Sequence of events in Experiments 1 and 2. (A) A green circle appeared when participants placed their fingers in the start location. **(B)** A picture of the to-be-pantomimed instructed action was shown, followed by **(C)** a distractor movie of the model pantomiming either the same or a different action. During AO **(C)** in Experiment 1 participants engaged in either synchronized MI or static MI. In Experiment 2 synchronization type was manipulated during AO [Synchronize the Instructed action (SI), Synchronize the Distractor action (SD), or Synchronize the Instructed action in the Orthogonal Plane (SIOP) with the distractor action], as was synchronization mode (synchronized MI or synchronized execution). For Experiment 2 only, a pause was inserted (**D**: red dot) to separate synchronized actions **(C)** from **(E)** later execution of the instructed action, which was cued by the appearance of a neutral, light-gray background.

EXPERIMENT 2

Participants

Fourteen new participants (6 male, mean age 24.1 years; SD = 7.6 years) volunteered for the study. All had normal ($n = 11$) or corrected-to-normal vision. Participants were naïve to the study's purpose, right-hand dominant (Edinburgh Handedness Inventory: $M = 74$; Oldfield, 1971), and without physical injuries. Written informed consent was obtained prior to participation, and ethical approval had been granted by Teesside University.

Stimuli and apparatus

The experimental setup and stimuli replicated those used in Experiment 1.

Procedures

Familiarization. Phases 1–3 were identical to those used in Experiment 1, and Phase 4 was extended. Since learning is a key component of the PETTLEP model for mental imagery training (Holmes and Collins, 2001), participants completed the Movement Imagery Questionnaire-3 (MIQ-3; Williams et al., 2012) prior to participating. They executed overt followed by imagined actions and then self-reported the vividness of their experiences on three subscales: visual internal, visual external and kinesthetic imagery (12 actions in total; mean scores = 5.4, 5.3, and 5.1/7, respectively). On each day of testing, an MI script based on the PETTLEP principles was read out, instructing participants to engage in internal, first person kinesthetic MI of the instructed actions (one habitually fast and one habitually slow). They then practiced the two synchronization modes (synchronized MI and synchronized execution: 4–8 trials) for each synchronization type (SI, SD, and SIOP see below) ahead of the related block of trials in the main experiment.

Main experiment. The trial structure is described in **Figure 6**. Participants were instructed to synchronize different actions with the distractor action. Instructions varied across blocks of trials as follows: (1) as in Experiment 1, participants Synchronized the Instructed action (SI) with the distractor movie; or (2) Synchronized the Distractor action (SD) with the distractor movie; or (3) Synchronized the Instructed action with the movie, but in the orthogonal plane (SIOP). Within each of the three conditions participants alternated between execution modes (synchronized MI or synchronized execution) across mini-blocks of eight trials. For synchronized execution, participants resumed the start position at distractor offset, wherein a red dot appeared for 2 s. This separated the distractor-synchronized action from the subsequently executed instructed action, wherein 3-D kinematics were tracked for 4 s.

Data analysis. In both Experiments mean cycle times (ms) were calculated between peak minimum kinematic positions using a customized signal processing application created in Microsoft Visual Studio. First, a 6 Hz low-pass, second order, bi-directional Butterworth Filter smoothed the data. For both horizontal and vertical actions, the first data point taken was the first peak minimum of the first movement cycle. This avoided analyzing hand movements during the initial spatial positioning phase for each action before a stable workspace was reached. Mean cycle time was calculated across all peak minimum positions available within a 2 s time window. Typically this involved either two or three cycles for habitually slow actions and four or five cycles for habitually fast actions. All trials with erroneous responses (incorrect or no action) were discarded (Experiment 1: $n = 10$; Experiment 2: $n = 63$).

The two main dependent measures used in Experiments 1 and 2 were the mean cycle time (ms) and the ratio (%) between slow and fast distractor trials. While the absolute difference between distractor cycle times was greater in the habitually slow actions (667 vs. 1000 ms) compared to the habitually fast actions (333 vs. 500 ms), the ratio of slow:fast distractor speeds was the same for each habitual speed (150%). For economy of exposition in both experiments, we restricted the analysis of the mean cycle time data to two factors of interest. We then analyzed the additional factors involved in each experiment using the cycle time ratios. Accordingly, the mean cycle times (ms) were analysed in both experiments using a two-factorial, repeated-measures ANOVA with the within-subjects factors of distractor speed (only available for this measure) and habitual speed. In Experiments 1 and 2 the cycle time ratios (%) were subjected to three- and four-factorial repeated-measures ANOVAs, respectively. The within-subjects factors involved in Experiment 1 were MI content, habitual speed, and compatibility (four levels). In Experiment 2 the four factors were synchronization mode, synchronization type, habitual speed, and action type compatibility (two levels).

We then used a pair of two-factorial mixed measures ANOVAs to compare the imitation bias that we obtained previously for passive AO (Eaves et al., 2012), to that which we obtained first for synchronized MI and second for static MI in Experiment 1. We then used similar analyses to compare these latter two conditions to the synchronized MI data from Experiment 2. In a final step, we used a series of simple main effect analyses to individually compare all 12 conditions in Experiment 2 to the fully-incompatible, and therefore most conservative, passive AO condition from our previous study (Eaves et al., 2012).

All analyses were conducted using SPSS Statistics 21 (IBM). Where appropriate, these were adjusted for any violation of the homogeneity of variance assumption using the Greenhouse–Geisser correction. Alpha levels were set to 0.05, and effect sizes were calculated as partial eta squared values (η_p^2). To reduce type I error rates, Fisher's least significant difference (LSD) contrasts were used in all pairwise comparisons, since four or less conditions were involved in each comparison (see Carmer and Swanson, 1973).

Reaction time data were also recorded to identify trials with anticipatory (<200 ms; Expt. 1: $n = 7$; Expt. 2: $n = 16$) or omission errors (>1300 ms; Expt. 1: $n = 2$; Expt. 2: $n = 7$), which were discarded from all analyses. In total, 1.2% (Expt. 1) and 4.2% (Expt. 2) of all trials recorded were removed from the analyses.

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Mirror training to augment cross-education during resistance training: a hypothesis

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Resistance exercise has been shown to be a potent stimulus for neuromuscular adaptations. These adaptations are not confined to the exercising muscle and have been consistently shown to produce increases in strength and neural activity in the contralateral, homologous resting muscle; a phenomenon known as cross-education. This observation has important clinical applications for those with unilateral dysfunction given that cross-education increases strength and attenuates atrophy in immobilized limbs. Previous evidence has shown that these improvements in the transfer of strength are likely to reside in areas of the brain, some of which are common to the mirror neuron system (MNS). Here we examine the evidence for the, as yet, untested hypothesis that cross-education might benefit from observing our own motor action in a mirror during unimanual resistance training, thereby activating the MNS. The hypothesis is based on neuroanatomical evidence suggesting brain areas relating to the MNS are activated when a unilateral motor task is performed with a mirror. This theory is timely because of the growing body of evidence relating to the efficacy of cross-education. Hence, we consider the clinical applications of mirror training as an adjuvant intervention to cross-education in order to engage the MNS, which could further improve strength and reduce atrophy in dysfunctional limbs during rehabilitation.

Keywords: mirror neuron system, rehabilitation, recovery, contralateral adaptations, strength training

BACKGROUND

A large body of evidence suggests that adaptations in elements of the central nervous system contribute to the responses to resistance training in the trained muscle (Enoka, 1988, 1997; Sale, 1988; Carroll et al., 2001; Aagaard et al., 2002). On a short time scale, adaptive responses in the trained muscle may occur even within one session of motor practice with correlated changes in motor performance and brain activation detected by transcranial magnetic brain stimulation (TMS) and imaging (Muellbacher et al., 2000; Foltys et al., 2003; Cincotta et al., 2004; Perez and Cohen, 2008; Sehm et al., 2010). On a longer time scale, there is now evidence that practice of elementary movements with loads ranging between 20 and 100% of maximum voluntary contraction at a wide range of contraction velocities cause adaptations in the excitability of spinal reflexes, corticospinal pathways, and cortical networks controlling the trained muscle (Carroll et al., 2011). These adaptation have been described independent of age, sex, and training status (Patten et al., 2001; Scaglioni et al., 2002; Kamen and Knight, 2004; Semmler et al., 2004; Kornatz et al., 2005; Ushiyama et al., 2010).

Curiously, neural adaptation to resistance training is not confined to the muscle(s) directly involved in exercise, but becomes expressed in a spatially specific manner in the contralateral homologous muscle in the form of increased voluntary force and neural activation (Hortobagyi, 2005; Carroll et al., 2006; Farthing, 2009). Effortful unilateral motor practice does not result in hypertrophy of the non-exercised contralateral limb muscle in healthy individuals (Hortobagyi et al., 1996a; Farthing et al., 2007), yet fascinatingly, the same exercise can somehow attenuate atrophy and/or strength loss in a disused muscle after short-term immobilization with (Magnus et al., 2013) or without a fracture (Farthing et al., 2009, 2011; Kidgell et al., 2011; Pearce et al., 2012). Another clinical manifestation of this inter-limb interaction is a reduction of muscle damage in a previously non-exercised limb caused by a single bout of eccentric-biased resistance exercise in the contralateral homologous muscle group (Howatson and van Someren, 2007; Starbuck and Eston, 2012). Collectively this adaptive response, commonly referred to as "cross-education," is the transfer of a motor ability to the contralateral, non-practicing homologous muscle following unilateral practice of a motor task or skill (Zhou, 2000; Lee and Carroll, 2007). The phenomenon suggests that when intact humans practice a unilateral motor task, the active practice on one side of the body can enhance the same motor behavior of the corresponding contralateral homologous muscle even though the muscle is not actively involved in the practice. Reported for the first time over 100 years ago in the psychomotor literature (Scripture et al., 1894), akin to the neural adaptations involved in activating the trained muscle, cross-education has been demonstrated under a variety of conditions along the skill continuum from elementary to complex motor tasks, independent of age, sex, and muscle (Zhou, 2000; Hortobagyi, 2005; Carroll et al., 2006; Lee and Carroll, 2007; Farthing, 2009). Intuitively one would expect that movements with an invariant time and spatial structure that normally make up resistance training would provide insufficient stimuli and produce little or no transfer. However, there is a broad range of evidence showing that repetition of elementary motor skills, as done during resistance training, reliably produces cross-education that is clinically and functionally meaningful (Cannon and Cafarelli, 1987; Hortobagyi et al., 1997; Munn et al., 2004; Farthing et al., 2007, 2011; Kidgell et al., 2011; Pearce et al., 2012; Magnus et al., 2013).

Experimental evidence supporting the strength- and muscle-sparing effects of cross-education during short-term immobilization in healthy individuals with (Magnus et al., 2013) and without (Farthing et al., 2009, 2011; Kidgell et al., 2011; Pearce et al., 2012) a fracture has renewed interest in cross-education as a possible adjuvant therapy in patients displaying unilateral orthopedic and neurological dysfunction. These preliminary findings are promising; however, the duration of dysfunction in many clinical populations can often be much longer than used in previous research and cross-education may not be as efficacious in other clinical groups. Considering that motor transfer occurs to a normally resting limb, it is not unexpected that the magnitude of cross-education was reported to be relatively small, <10% (Munn et al., 2004; Carroll et al., 2006). However, since these publications, evidence from other groups has emerged that lend greater weight to the intervention; these will be discussed in greater detail below. Because of its clinical potential, however, the question is whether there is a mechanism that could augment the magnitude of transfer. Given that sensory feedback during motor practice can increase motor output, one possibility is to activate neurons involved in the transfer that might also be activated by other means, thereby resulting in a synergistic effect on transfer.

In recent investigations (Farthing et al., 2007, 2011; Hortobagyi et al., 2011; Carson and Ruddy, 2012) there is evidence that cross-education following strength training increases brain activation in areas that overlap with areas containing mirror neurons. Mirror neurons are neurons that are activated both during perception and during execution of a motor action (Rizzolatti et al., 1996; Rizzolatti and Craighero, 2004; Iacoboni, 2005). Here we examine the possibility that the mirror neuron system (MNS) could be involved in cross-education and hypothesize that observing the exercising limb in a mirror would augment the magnitude of cross-education. In support of this hypothesis, we provide an overview of the MNS and the evidence surrounding the adaptive response to resistance exercise in cross-education paradigms. More importantly, we present ideas how a mirror might augment these adaptive responses and examine the evidence from brain imaging and stimulation studies that report how observation, imagery and execution of elementary motor tasks modulate brain activity. Finally we review preliminary evidence supporting the role of cross-education in unilateral orthopedic and neurological conditions.

OVERVIEW OF THE MIRROR NEURON SYSTEM

The MNS consists of a complex network of neurons distributed over several cortical areas of the brain and provides a neuroanatomical basis for the development of motor learning and skill acquisition, whereby a motor act can be learned and facilitated by observing and imitating the act (Rizzolatti et al., 1999; Rizzolatti and Craighero, 2004; Iacoboni, 2005). The MNS is thought to be important for the development of motor skills and its existence was originally demonstrated in primates (di Pellegrino et al., 1992) and later in humans (Grafton et al., 1996; Rizzolatti et al., 1996). There is a great deal of homology between the primate and human brain, especially in the premotor cortex (Rizzolatti and Craighero, 2004; Small et al., 2012); consequently, primate models provide clues to understanding how the MNS works in primates and also in humans as detailed in comprehensive reviews (Rizzolatti and Craighero, 2004; Rizzolatti and Fabbri-Destro, 2010). The MNS connects neurons responding to visual properties of an observed task with neurons that discharge action potentials when a similar task is executed. In brief, the key points are that the MNS neurons are activated by perceptual input, self-observation of a motor act, observation of a third party's movement, imitation of a motor act, and by movement execution (di Pellegrino et al., 1992; Heyes, 2010; Ray and Heyes, 2011) that are common in the arts and resistance exercise. The MNS comprises of neuronal networks in the visual areas of the parietal, occipital and temporal lobes (Rizzolatti and Craighero, 2004). Areas predominantly activated by motor acts are also core to the MNS in humans (Rizzolatti and Craighero, 2004) and include the inferior parietal gyrus, pre-central gyrus, and inferior frontal gyrus (Rizzolatti et al., 1996; Iacoboni et al., 1999, 2001; Ray and Heyes, 2011).

Observation and execution of motor acts both activate neurons belonging to the MNS. During simple or over-learned tasks, visual information is processed in the superior temporal sulcus (STS) and then sent to the frontoparietal area of the MNS where coding for that specific motor programme occurs. The motor programme is then copied and transferred to the STS where the visual description of the task is compared to the expected sensory consequences of the imitated actions (Iacoboni et al., 1999; Iacoboni, 2005). Prior motor experience is essential (Beudel et al., 2011) and can engage and modulate the MNS, because dancers and musicians, compared with naïve participants, revealed greater mirror activation while observing someone playing an instrument or dancing (Heyes, 2010). Interestingly, when novel tasks are performed there is involvement of additional areas in motor preparation, such as middle frontal gyrus (Rowe et al., 2000), dorsal premotor cortex, superior parietal gyrus and caudal frontal gyrus (Buccino et al., 2004a). Critically, some areas that broadly relate to pars opercularis; namely the ventral premotor cortex, inferior frontal gyrus, inferior parietal lobule are important in adaptive responses and have motor properties that are activated when observing motor actions in a mirror (Molenberghs et al., 2012). To summarize, the frontopariental and STS are involved in the MNS, but additional areas also appear to be implicated when the task is more novel. In the following section, we present evidence suggesting that areas of the brain involved in the MNS might also be associated in cross-education.

CROSS-EDUCATION FOLLOWING RESISTANCE EXERCISE

The transfer of enhanced force-generation to the contralateral homologous "resting" muscle (i.e., cross-education) appears to be influenced by brain areas that are also common with those involved in the MNS. The basis for cross-education with chronic training is that motor areas in both hemispheres become concurrently active during a unilateral muscle contraction, demonstrated by cross-sectional transcranial magnetic brain stimulation (TMS), electroencephalography (EEG) and imaging studies (Kristeva et al., 1979; Cramer et al., 1999; Newton et al., 2002; Zijdewind et al., 2006; Howatson et al., 2011). Many participants show "associated" electromyographic (EMG) activity in the resting muscle during unilateral contractions (Zijdewind and Kernell, 2001; Zijdewind et al., 2006; Sehm et al., 2010). As the performance improves with unilateral resistance training, it is thought that this practice repeatedly excites the relevant brain areas and motor programmes for that task, and become accessible to networks that control the contralateral homologous resting muscle (Carroll et al., 2006; Farthing et al., 2007; Lee and Carroll, 2007; Lee et al., 2009; Hortobagyi et al., 2011).

In one example, participants performed 6 weeks (21–24 sessions) of maximal isometric ulnar deviations with the right arm. Maximal strength increased by 45 and 47% for the trained and untrained arm, respectively. The interpretation was that training modified brain activation and communication between hemispheres, whereby an improved motor plan [from training] provided the untrained brain areas with a reference for preparation and execution for movements (Farthing et al., 2007). Evidence supporting this interpretation comes from accompanying fMRI data showing enlarged regions of activation in the contralateral "trained" left temporal lobe, premotor and visual cortices and "untrained" sensorimotor cortex and primary motor cortex (M1) when participants contracted the homologous muscles of the untrained limb in a magnet (Farthing et al., 2007, 2011). Critically, although the left temporal lobe (especially the STS) and other aforementioned structures appear to be involved in cross-education and the MNS, there is as yet, no direct evidence that the same networks implicated in the MNS are concurrently activated in cross-education. In a separate TMS study, 1000 voluntary isometric contractions of the first dorsal interosseus (at 80% of maximum force, distributed over 20 sessions) increased the excitability of the "untrained" (M1) and decreased interhemispheric inhibition (IHI) by 31% from the trained to the untrained M1. The reduction in IHI correlated with the 28% cross-education (Hortobagyi et al., 2011). Presumably the anterior fibers of the corpus callosum (a structure not implicated in the MNS) mediated such interhemispheric effects between the "trained" and "untrained" frontal motor areas—structures that are involved in the MNS. Indeed, the corpus callosum (specifically the transcallosal pathways) plays a role within the cortical network in promoting a consolidated experience that integrates our perceptions and preparation of our actions (Schulte and Muller-Oehring, 2010). By inference, following training of muscle groups on the right side, when the right sensorimotor cortex and left temporal lobe are implicated in cross-education (reduced IHI) of the muscle groups of the left side, it remains a plausible hypothesis that the MNS is involved since the same brain areas are activated.

HOW MIGHT THE USE OF A MIRROR AUGMENT THE CROSS-EDUCATION EFFECT?

Although the exact mechanisms underpinning cross-education following resistance exercise are not fully understood, experimental data in both primates and humans make the expectation tenable that unilateral motor practice (specifically resistance exercise) and cross-education could be enhanced with a mirror. Mirror training involves a superimposed, reflective image of the exercising limb projected on to the non-exercising limb and thereby giving the appearance that the "resting" side is actually active (Matthys et al., 2009; Nojima et al., 2012; Small et al., 2012). Mirror training can increase ipsilateral brain activity (Garry et al., 2005; Matthys et al., 2009), reduce phantom limb pain (Ramachandran et al., 1995; Ramachandran and Rogers-Ramachandran, 1996) enhance recovery of motor function following stroke (Sutbeyaz et al., 2007; Yavuzer et al., 2008) and improve skill acquisition of the non-practiced hand in healthy participants (Hamzei et al., 2012; Lappchen et al., 2012; Nojima et al., 2012). In this section we explore ideas that the overlap between brain areas involved in cross-education and the activation of the MNS might synergistically augment the effect of cross-education with a mirror whilst resistance training.

During a unilateral muscle contraction, there are at least two sources of neural activation that could play a role in the strength- and atrophy sparing effects associated with cross-education. One is the "associated activity" that appears in the resting limb during motor practice with the other limb. The magnitude of the "associated activity" can reach 20% of MVC (Hortobagyi et al., 1997; Zijdewind and Kernell, 2001; Zijdewind et al., 2006) and there is some evidence that resistance exercise at an intensity as low as 10% can improve muscle function (Laidlaw et al., 1999; Duchateau et al., 2012; Kobayashi et al., 2012). Although the source of this "associated activity" is uncertain, it is likely to arise from the hemisphere driving the muscle contraction (Devanne et al., 1997; Zijdewind et al., 2006); repeated and concurrent activation of the motor area controlling the transfer hand could serve a second source for the strength- and muscle-sparing effects seen in cross-education studies (Farthing et al., 2009, 2011; Pearce et al., 2012). As the MNS has overlapping neuroanatomical brain structures with those activated in cross-education, the possibility exists that observing the image of the moving limb in a mirror increases the magnitude of brain activity controlling the resting limb and potentially, the "associated activity" inside the cast.

How such inadvertent brain activity can increase MVC force of the untrained or casted hand is unclear, but one possibility is that the repeated activation of these motor cortical areas changes the threshold of a so far un-recruited subliminal "fringe" of cortical neurons or that the gain of the active neurons increases (Gardiner, 2006). Both would create greater drive during the MVC after the training programme. The use of a mirror during the training could increase the amount of associated activity by engaging the MNS and thus result in a larger training effect. In essence, the use of a mirror creates an action observation effect (discussed in greater detail in the subsequent section) and prime cortical neurons to become more active. Because changes in the maximum slope and threshold of TMS recruitment curves after an intervention reflect the changes in the size of the subliminal fringe (Devanne et al., 1997), it is possible to test whether this mechanism is involved in cross-education (Hortobagyi et al., 2011) and if mirror training amplifies the cross-education effect through this mechanism.

Another possibility for the use of a mirror to augment the transfer effects is an increase in cortical plasticity within and between hemispheres that is evident following unilateral resistance training (Goodwill et al., 2012), thereby further enhancing connectivity following training. In addition, neurons responsible for motor function in the untrained hemisphere that were excitable, but not beyond the point of threshold before training, might be subject to an adaptive response, such that the threshold is either reduced or the corticospinal excitability is increased to the targeted motor neurons and thereby allowing the critical threshold point to be reached, which was not possible before the training. This is conceivable because the magnitude of IHI (Hortobagyi et al., 2011) and short interval intracortical inhibition (SICI) (Hortobagyi et al., 2011; Goodwill et al., 2012) in the untrained cortical hemisphere is attenuated with cross-education effects produced by resistance training. These could be the mediating mechanisms, at least in part, allowing these neurons to reach that "critical" threshold level during and following training, which is akin to theories relating to "motor overflow" (Hoy et al., 2004). Furthermore, imaging studies suggest that previously quiescent areas of the brain become active following unilateral resistance training in the non-trained hemisphere (Farthing et al., 2007). Given the apparent overlap in brain areas of the MNS and those involved in cross-education, the magnitude of response could be further enhanced by specifically activating areas of the MNS by observing the actions of the active limb in a mirror.

The exact mechanisms for these strength increases following cross-education are yet to be elucidated; however, there is the suggestion that the MNS is involved with healthy (Matthys et al., 2009; Nojima et al., 2012) and clinical (Rosen and Lundborg, 2005; Sutbeyaz et al., 2007) populations. Like unilateral resistance training, it seems that mirror training of the right limb (i.e., seeing the mirror image of the exercising right limb) increases the size of the activated brain regions in the ipsilateral (right) M1 (Garry et al., 2005; Nojima et al., 2012), but without causing changes in IHI from the contralateral (left) to the ipsilateral (right) M1 or SICI in the ipsilateral M1 (Nojima et al., 2012). Furthermore, Lappchen et al. (2012) showed increased SICI in the contralateral (left) M1 following right handed skill training with the use of a mirror, which was accompanied by decreased SICI in the ipsilateral (right) M1. This apparent discrepancy in SICI may be due to differences in training duration; Nojima et al. (2012) used a single day as opposed to Lappchen et al. (2012) who conducted 4 days of training, suggesting SICI has a role in the effects of cross-education of skilled motor acts augmented with mirror training. In addition to the ipsilateral (right) M1 (Shinoura et al., 2008; Carson and Ruddy, 2012; Nojima et al., 2012), the right SMA, occipital lobe and cerebellum (Shinoura et al., 2008), and contralateral (left) STS, superior occipital gyrus (Matthys et al., 2009) and M1 (Garry et al., 2005; Shinoura et al., 2008; Tominaga et al., 2011) are involved in mirror training with the right upper extremity. Brain areas that became increasingly active after a short period of mirror training of the right hand were the contralateral (left) inferior parietal lobe and ventral premotor cortex and the ipsilateral (right) dorsal premotor cortex (Hamzei et al., 2012). Enlarged activation areas of the STS, occipital cortex, inferior parietal lobe, premotor areas and the M1 provide links between the MNS, mirror training and performance improvement. It is intuitively appealing to presuppose that combining cross-education with mirror training would stimulate synaptic interactions and thereby strengthen the connections within multiple cortical regions that are known to be involved in the MNS and cross-education, and hence leading to greater levels of cross-education.

The information presented here suggests that adaptations transferred from the practiced "contralateral" brain regions to untrained "ipsilateral" brain regions, activate different networks dependent upon whether they are performed with or without a mirror (Lappchen et al., 2012). Whilst cutaneous and proprioceptive inputs are important and can influence the magnitude of intracortical and interhemipsheric inhibition (Swayne et al., 2006), visual information in the form of a mirror could conceivably facilitate the transfer of strength in a cross-education resistance training model. We suspect from neuroanatomical, electrophysiological, imaging and EEG data that mirror training may be a useful tool to augment the effects of cross-education of strength; however, there are currently no experimental studies that have specifically tested this hypothesis. In the following section we explore the evidence for brain activation during action observation, imagery and the execution of the task.

BRAIN ACTIVATION DURING MOVEMENT OBSERVATION, IMAGERY AND TASK EXECUTION

Mirror and imagery training create their effects based on illusionary actions of the resting limb. The inter-limb effects produced by cross-education supplemented with a mirror or done through imagery (Yue and Cole, 1992) would rely on mechanisms also involved in action observation. Many of the areas suggested to have mirror properties, also become active during motor imagery (Grezes and Decety, 2001; Jeannerod, 2001). Jeannerod (2001) described in his "simulation theory" that motor actions have a covert state and both movement observation and motor imagery are covert motor actions. In other words, movement observation and motor imagery are motor actions that have not been executed but that use the same neuronal substrates as the actual performance. Hence, as mentioned briefly in the previous section, movement observation and motor imagery result in subliminal facilitation of neurons that belong to the motor network or, alternatively, the activation of the motor network is actively inhibited before the movement is executed (Jeannerod, 2001; Guillot et al., 2008). Several studies, summarized in reviews, have reported an overlap of brain activation during movement observation and execution (Grezes and Decety, 2001; Jeannerod, 2001; Caspers et al., 2010; Molenberghs et al., 2012) and between motor imagery and execution (Decety, 1996; Grezes and Decety, 2001; Jeannerod, 2001; Munzert et al., 2009). Meta-analyses (Munzert et al., 2009; Caspers et al., 2010; Molenberghs et al., 2012) showed that besides cortical areas that "traditionally" belong to the MNS (ventral premotor area and inferior parietal cortex) action observation and execution involved a bilateral network that comprised premotor, primary somatosensory, inferior parietal, intraparietal and temporo-occipital areas.

The primary motor cortex also shows activity during both motor imagery (Pfurtscheller and Neuper, 1997; Porro et al., 2000; Boeker et al., 2002; Lotze and Halsband, 2006) and motor observation (Molenberghs et al., 2012), albeit less pronounced and its activation is not due to typical mirror neuron activity. The involvement of the corticospinal tract in motor imagery (Kiers et al., 1997; Fadiga et al., 1999; Rossini et al., 1999; Facchini et al., 2002; Fourkas et al., 2006; Roosink and Zijdewind, 2010; Lebon et al., 2012) and movement observation (Fadiga et al., 1995; Rossini et al., 1999; Brighina et al., 2000; Patuzzo et al., 2003; Clark et al., 2004; Roosink and Zijdewind, 2010) has been confirmed with TMS. In single-pulse TMS paradigms, neurons in the motor cortex are activated and modulations in the excitability of the corticospinal tract affects the amplitude of the motor evoked potential (MEP). Many experiments have demonstrated that during movement observation and motor imagery the MEP amplitude is modulated in an effector and task specific manner (Fadiga et al., 1995; Rossini et al., 1999; Facchini et al., 2002; Stinear and Byblow, 2003; Roosink and Zijdewind, 2010; Lebon et al., 2012). Therefore, there is indirect evidence suggesting that the use of a mirror in cross-education interventions could augment the inter-limb transfer through a higher activation of M1 and the corticospinal tract during contraction of the untrained muscles after training.

Although movement observation and imagery activate similar brain areas, the magnitude of activation during observation and imagery is not similar; TMS studies showed differences in the contribution and timing of the corticospinal tract to the effects produced by observation and imagery. Comparisons between TMS evoked responses during movement observation and imagery showed increased activation (Cattaneo and Rizzolatti, 2009; Roosink and Zijdewind, 2010), no difference (Patuzzo et al., 2003; Clark et al., 2004; Leonard and Tremblay, 2007), or decreased activation (Fuerra et al., 2011) during movement observation. Part of these differences could be explained by the use of different tasks; task-specific activation, for instance, increases with task complexity. During execution of a complex motor task, stronger activation foci are seen in the contralateral sensorimotor cortex (Catalan et al., 1998; Kuhtz-Buschbeck et al., 2003), bilateral posterior SMA (Catalan et al., 1998), dorsal premotor area and ipsilateral cerebellum (Catalan et al., 1998; Kuhtz-Buschbeck et al., 2003). Furthermore, single pulse and repetitive TMS studies underline the larger contribution of both the contralateral (Abbruzzese et al., 1996; Gerloff et al., 1998; Roosink and Zijdewind, 2010) and ipsilateral motor cortex (Tinazzi and Zanette, 1998) during complex motor tasks. These data suggest that mirror-aided cross-education studies using complex motor tasks would most likely produce greater inter-limb effects; a hypothesis we are currently exploring using a model that incorporates high intensity resistance training coupled with simple and complex visuomotor skills (i.e., with and without a mirror).

In addition to task complexity, the intensity of muscle contraction also modulates brain activation of the motor areas (Dettmers et al., 1995; van Duinen et al., 2008) and its excitability (Hess et al., 1986; Tinazzi and Zanette, 1998). During observation of tasks that require increased force levels, MEPs produced by TMS increase with the increasing levels of force (Alaerts et al., 2010a,b). The quality of and being an expert in imagery determines which brain areas become active (Guillot et al., 2008) and the intensity of the (subliminal) corticospinal activity (Lebon et al., 2012). Those with high imagery ability showed increased activation of parietal and ventrolateral premotor gebieden; low imagery performers cerebellum, orbito-frontal and posterior cingulated cortices. TMS data also suggests that good, compared with poor imagers, had greater facilitation of the target muscles (Lebon et al., 2012; Williams et al., 2012). Furthermore, skillful vs. less able imagers showed a stronger temporal and spatial modulation of the corticospinal excitability (Lebon et al., 2012). In other words, poor imagers demonstrated a general increase in corticospinal activity that was less focused with respect to timing and the specificity of muscle(s) activation. Furthermore, instructions to the participant are critical; action observation in a passive manner compared to action observation with the intent to imitate, result in similar but weaker fMRI activation (Decety et al., 1997; Grezes et al., 1999; Buccino et al., 2004b; Frey and Gerry, 2006). This observation is also underlined by TMS experiments that showed that the MEP facilitation was larger in the observation to-imitate condition (Roosink and Zijdewind, 2010). Finally, the position of the effector during imagery also affects corticospinal excitability (Vargas et al., 2004; Fourkas et al., 2006). These TMS studies showed a larger facilitation of MEPs when the position of the effector was congruent with the "to-imagine" movement.

Overall these data suggest the action observation elements of mirror-aided cross-education have exciting clinical potential, as long as the intervention conditions are optimized for the population and the individual. Observing one's own movements in a mirror during cross-education therapy is expected to be especially effective if the motor task is challenging, the spatial orientation of the practicing and non-practicing limbs are similar, patients are highly motivated and engaged in the action observation task, and if the act of observation is combined with imagery of the target hand moving (Stefan et al., 2008). In line with these arguments, the subsequent section presents data for the clinical efficacy of cross-education and how this effectiveness could be further increased by the use of a mirror.

CLINICAL APPLICATIONS OF CROSS-EDUCATION AND FACILITATION WITH MIRROR-TRAINING

A peculiar phenomenon associated with cross-education is that unilateral motor practice does not produce morphological changes in muscles of the non-exercised contralateral limb (Hortobagyi et al., 1996b), yet the same exercise can somehow attenuate skeletal muscle atrophy and/or strength loss in the immobilized limb with (Magnus et al., 2013) or without (Farthing et al., 2009, 2011; Kidgell et al., 2011; Pearce et al., 2012) a fracture. These observations suggest that atrophied and/or injured compared with healthy muscles are more sensitive to neural activation. This section explores firstly, the evidence and application of cross-education in clinical populations and secondly, proposes that the use of mirror therapy might further augment the benefits of strength transfer and attenuate atrophy.

The cross-education effect has long been identified as a potential therapeutic strategy during rehabilitation from unilateral injury or neurological dysfunction. Yet until the recent work on the efficacy of cross-education after wrist fractures (Magnus et al., 2013), ACL surgery (Papandreou et al., 2013) and in post-stroke recovery (Dragert and Zehr, 2013) there was little evidence in patient populations to substantiate this claim. An early attempt by Stromberg (1986, 1988) to apply cross-education during post-operative therapy after various hand and wrist surgeries was not well-controlled and limited by no reporting of pre-surgery status for either limb. Thus, the study received little attention, with misleading reporting of better post-surgery outcomes for the cross-education group. The idea received little further attention until promising evidence emerged from immobilization studies in healthy intact participants, where cross-education was shown to have a strength and muscle sparing effect for the opposite the immobilized arm (Farthing et al., 2009, 2011; Pearce et al., 2012). Unilateral motor practice is not known to produce morphological changes in muscles of the non-exercised contralateral limb, yet strangely, the same exercise can attenuate atrophy in the immobilized limb (Farthing et al., 2009, 2011; Kidgell et al., 2011; Pearce et al., 2012). These observations suggest that atrophied compared with healthy muscles are more sensitive to the effects of neural activation, and the threshold of activity needed to prevent short-term atrophy is much less than is needed to stimulate hypertrophy.

Although the precise mechanisms of the sparing effects remain unclear, Farthing et al. (2011) reported after training of the right limb there was increased activity in contralateral (right) motor cortex and ipsilateral (left) premotor and visual cortices during contractions of the previously immobilized (left) limb; areas that are also associated with the MNS. Pearce et al. (2012) reported unaltered corticospinal excitability and strength maintenance for the immobilized arm of participants who trained the non-immobilized limb, whereas MEP amplitude at various intensities was decreased by ~20% for non-training participants. The data from immobilization models of injury in healthy participants revitalized interest in cross-education as a viable, untested clinical intervention, but lack of patient data remained a key limitation.

Building on the arm immobilization models, there is new evidence that cross-education can benefit the recovery of strength and mobility following wrist fractures. Magnus et al. (2013) implemented unilateral strength training of the non-fractured limb (3 times per week, progressing to 40 maximal efforts per session) within 1-week post-fracture, in addition to standard rehabilitation, in women over the age of 50 who suffered a distal radius fracture. The outcomes for the fractured limb were compared to patients receiving standard rehabilitation alone. The training group had significantly greater fractured limb handgrip strength (~47%) and active range of motion (~25%) at 12 weeks post fracture compared to the control group. Unfortunately, the study was inconclusive for patient's self-rated function scores and there were no measures of muscle or brain activation, or cortical or spinal excitability. However, given there is evidence of increased EMG activity in the non-exercising limb during cross-education studies (Hortobagyi et al., 1997; Zijdewind and Kernell, 2001; Zijdewind et al., 2006), one possibility is that the level of "associated activity" is even greater in the muscle inside the sling or cast during unilateral motor practice than the customary cross-education studies. Notwithstanding, the study is the first to demonstrate the benefit of cross-education in an orthopedic clinical setting involving immobilization. Although the study targets a specific population at higher risk for wrist fractures, the results support the notion that cross-education is probably useful in a broad range of orthopedic injuries that involve unilateral immobilization after a fracture (Farthing et al., 2009, 2011; Kidgell et al., 2011; Pearce et al., 2012).

In addition to the data from wrist fractures, Papandreou et al. (2013) tested cross-education as an adjunct therapy in addition to bilateral strength training to combat quadriceps strength deficit after recovery from anterior cruciate ligament (ACL) reconstructive surgery, in young male soldiers (age 20–25 years) with a recent ACL injury (40 days to 6 months prior). The intervention was eccentric training of the uninjured leg, either 3 or 5 days per week for 8 weeks, using 5 sets of 6 contractions at 80% of 1 RM, completed in addition to a traditional ACL rehabilitation program for both legs (including strength, ROM, balance, and endurance training). Outcomes for the injured leg were compared to a control group who participated in the traditional ACL rehabilitation program only. Although there were no differences between the groups for changes in absolute strength, the cross-education intervention of either 3 or 5 days per week was effective for decreasing the between-leg quadriceps deficit (by ~12% and 17%, respectively) compared to the control group (24%). The studies by Papandreou et al. (2013) and Magnus et al. (2013) support the notion that cross-education is a useful adjunct therapy for a broad range of unilateral orthopedic injury.

Unilateral strength training of the less-affected limb can facilitate bilateral neural plasticity in chronic stroke patients. Dragert and Zehr (2013) demonstrated that intense training of the less-affected dorsiflexor muscles resulted in significant strength gains of 34% for the less-affected limb and 31% for the more-affected untrained limb. The improvements in strength were accompanied by significant gains in dorsiflexor muscle activation, altered reciprocal inhibition, and improved gait speed in a functional walking test. Perhaps most importantly, prior to the intervention four participants were unable to generate functional dorsiflexion in the more-affected limb, but were able to after training of the less-affected limb. This study marks the first evidence that cross-education is a viable strategy to improve bilateral function in a chronic stroke group, particularly when the more-affected limb is initially too weak to train.

Taken together, the wrist fracture, knee surgery, and post-stroke cross-education studies mark important translational advances in the field. As proof-of-principle works, the interventions involved basic isometric strength training or eccentric training of one target muscle group without the use of additional therapeutic strategies such as a mirror. The hypothesis that mirror-facilitated cross-education of strength training would enhance the therapeutic benefit is tenable for both the orthopedic injury and stroke rehabilitation environment. Mirror training has been shown to increase ipsilateral brain activity (Garry et al., 2005; Matthys et al., 2009) enhance skill performance in the resting, non-practiced hand of healthy participants (Hamzei et al., 2012; Lappchen et al., 2012; Nojima et al., 2012), accelerate motor recovery in stroke (Sutbeyaz et al., 2007; Yavuzer et al., 2008), and reduce phantom limb pain (Fadiga et al., 1999; Fourkas et al., 2006). The concept of mirror-assisted cross-education operates on the premise of the illusion that there is more movement in affected or injured limb (by viewing the mirror image of the less-affected or uninjured limb executing intense dynamic strength exercise), and this would further engage common brain areas involved in the MNS (Rosen and Lundborg, 2005; Sutbeyaz et al., 2007; Matthys et al., 2009; Nojima et al., 2012) and further stimulate neural plasticity to augment functional recovery. Unilateral strength (Dragert and Zehr, 2013) and skill training (Ausenda and Carnovali, 2011) of the less-affected limb, and mirror training (Yavuzer et al., 2008; Michielsen et al., 2011) have been shown, independently, to induce bilateral neural plasticity in post stroke rehabilitation. Merging the consequentially enhanced activation of the "ipsilateral" M1 (Garry et al., 2005; Nojima et al., 2012) by mirror training and the known reductions in IHI with chronic unilateral strength training (Hortobagyi et al., 2011) remains a logical next step; albeit firstly in intact participants.

For orthopedic injuries the hypothesis is viable with emerging evidence for the sparing effects in an immobilized fractured limb (Magnus et al., 2013), but there is only sparse clinical case study support for the use of mirror training to re-establish function after cast removal post wrist fracture (Altschuler and Hu, 2008) or after hand surgery (Rosen and Lundborg, 2005). The implementation of mirror training in either context would predictably alter the level of "associated activity" of the opposite affected limb. The associated activity of the fractured limb beneath the cast, during strength training of the non-fractured limb was not examined in the clinical study by Magnus et al. (2013), but the co-activation of more-affected dorsiflexors during training of the less-affected dorsiflexors in stroke patients was reported as 22% post-intervention (Dragert and Zehr, 2013). The associated activity in the resting limb of healthy participants can be as high as 20% of MVC (Hortobagyi et al., 1997, 2011; Zijdewind and Kernell, 2001; Zijdewind et al., 2006), but is commonly around 10% MVC, is position dependent (Post et al., 2009) and diminishes with chronic unilateral training (Hortobagyi et al., 2011). Muscle over-activity and co-activation has been documented post-stroke (Gracies, 2005), which might explain higher levels of post-intervention associated activity reported by Dragert and Zehr (2013). The origin of the associated activity and the clinical relevance of enhancing or reducing this activity during rehabilitation of an injured limb, or a neurologically impaired limb post-stroke are unclear. The hypothesis of augmented cross-education effects by use of a mirror is an exciting premise for future intervention studies in both healthy, and more importantly, clinical populations.

Although the idea surrounding the use of mirror training to engage the MNS and augment cross-education is appealing; the possibility equally exists that the mirror training might not work in further facilitating the response, especially in a patient population. As previously mentioned, patient need a sufficiently challenging task, similar orientation of the practicing and non-practicing limb, be highly motivated and engaged in the observation task, and perhaps combined with imagery of the target hand moving (Stefan et al., 2008). It could be that patient groups are unable to fulfill these requirements because of underlying pain, discomfort, motivation and limb orientation, and hence might compromise the patient's ability to effectively engage in such an action observation task. In addition, it is conceivable that the CNS might prioritize instead of augment activation when using a mirror or that the injury or dysfunction affects sensory pathways involved in mediating the engagement of the MNS.

GENERAL SUMMARY

In summary, resistance exercise is a potent stimulus for adaptations in the neuromuscular system. These adaptations are not confined to the exercising muscle and can produce clinically meaningful increases in strength and neural activity in the contralateral, homologous resting muscle. Evidence has shown that these improvements in the transfer of strength are likely to reside in the central nervous system in areas of the brain that are common to the MNS. Given the clinical relevance and importance of this application, we provide a neuroanatomical basis for the, as yet, untested hypothesis that cross-education could be enhanced by augmented sensory feedback using a mirror superimposing the reflected image of the exercising muscle to the non-exercising side and thereby giving the appearance the "resting" side being active. Enhanced cross-education by engaging the MNS with the use of a mirror could improve neuromuscular functionality and the clinical prognosis of many pathologies and is an area worthy of further scientific enquiry. This has the scope to, not only improve strength and reduce atrophy in immobilized limbs during rehabilitation, but also to improve execution of everyday tasks like buttoning shirts, threading needles in other challenged populations.

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