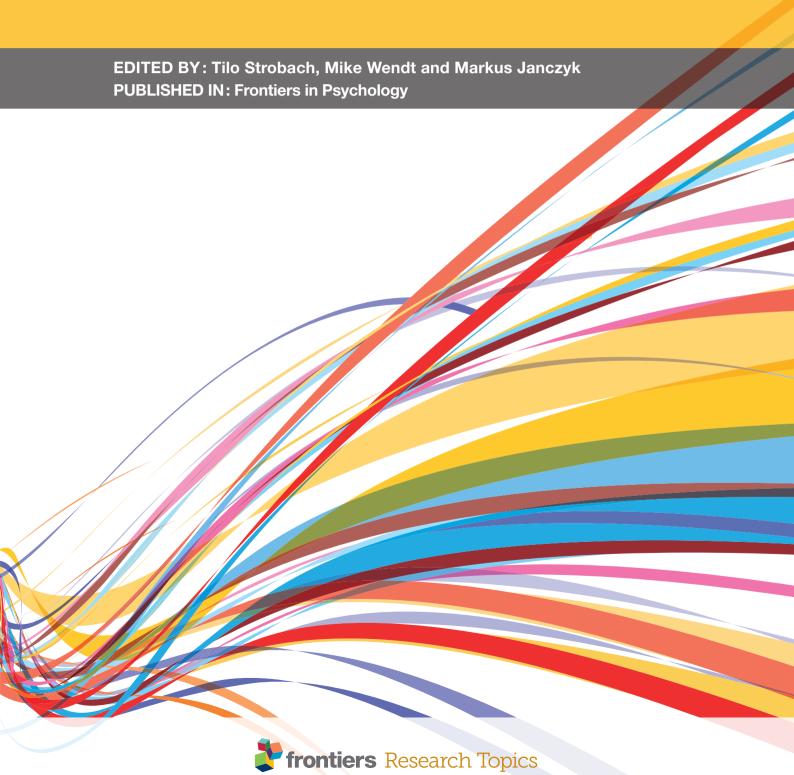
# MULTITASKING: EXECUTIVE FUNCTIONING IN DUAL-TASK AND TASK SWITCHING SITUATIONS





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# MULTITASKING: EXECUTIVE FUNCTIONING IN DUAL-TASK AND TASK SWITCHING SITUATIONS

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Multitasking refers to performance of multiple tasks. The most prominent types of multitasking are situations including either temporal overlap of the execution of multiple tasks (i.e., dual tasking) or executing multiple tasks in varying sequences (i.e., task switching). In the literature, numerous attempts have aimed at theorizing about the specific characteristics of executive functions that control interference between simultaneously and/or sequentially active component of task-sets in these situations. However, these approaches have been rather vague regarding explanatory concepts (e.g., task-set inhibition, preparation, shielding, capacity limitation), widely lacking theories on detailed mechanisms and/ or empirical evidence for specific subcomponents. The present research topic aims at providing a selection of contributions on the details of executive functioning in dual-task and task switching situations. The contributions specify these executive functions by focusing on (1) fractionating assumed mechanisms into constituent subcomponents, (2) their variations by age or in clinical subpopulations, and/ or (3) their plasticity as a response to practice and training.

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## **Editorial: Multitasking: Executive Functioning in Dual-Task and Task Switching Situations**

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#### **Editorial on the Research Topic**

#### Multitasking: Executive Functioning in Dual-Task and Task Switching Situations

Persons are often engaged in activities that combine multiple tasks (so called *multitasking*), even though this combination is typically accompanied by performance costs in the individual tasks in comparison to their performance as single tasks. Such performance costs suggest that performing multiple tasks brings the cognitive processing system to its limits. However, the observed limitations can inform theories of how cognitive processing is generally organized. In other words, investigations on the limitations of multitasking performance can reveal fundamental aspects of the cognitive processing architecture and mechanisms of human information processing.

These aspects have been investigated with a variety of experimental paradigms typically comprising two different component tasks that vary in the degree of temporal overlap. While it is difficult to define with precision what constitutes a "task" (Rogers and Monsell, 1995; Monsell, 2003; Kiesel et al., 2010), one can define "task" broadly, so that (i) simple stimulus-response (S-R) translations [e.g., press a response key when hearing a low tone in so-called choice reaction time (RT) tasks], (ii) continuous tasks like motor tracking, (iii) complex movements (e.g., type writing), or (iv) tasks without necessarily yielding overt behavior (e.g., counting) can constitute a task if a person aims to achieve a discriminable goal state. Irrespective of the specific type of task, multitasking research includes research on dual-task performance and task switching performance (Pashler, 2000). While dual-task performance requires concurrent and simultaneous task processing and motor responses, task switching focuses on multitasking with sequentially processed component tasks.

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## **DUAL-TASK PARADIGMS, THEORIES, AND EXECUTIVE FUNCTIONING**

Generally speaking, there are two paradigms to investigate dual-tasking. In the simplest version, dual-task performance is compared with single-task performance, with only one stimulus/task being presented in the latter condition. Notably, in this paradigm, there is either a single stimulus or two simultaneous stimuli at the same time, and task load is manipulated in a one-vs.-two manner. In other words, participants either perform one task or two tasks per block. Dual-task performance

costs are reflected in worse performance in dual- compared with the single-task conditions (e.g., Fagot and Pashler, 1992; Huestegge and Koch,  $2009)^1$ .

A second dual-task paradigm employs (most often) two choice RT tasks and varies the amount of temporal overlap of the two tasks. This overlapping task paradigm is nowadays often referred to as the Psychological Refractory Period (PRP) paradigm (Welford, 1952; Pashler and Johnston, 1989; Pashler, 1994). More specifically, stimuli of the two tasks are presented in a predictable order separated by a variable stimulus onset asynchrony (SOA). With short SOA (e.g., 50 ms), task overlap is high while with a long SOA (e.g., 1,000 ms) task overlap is low. Typically, RTs of Task 2 increase, the shorter the SOA between both tasks are (i.e., the PRP effect; see Janczyk et al., 2014, for exceptions to the PRP effect), while the SOA has no or only a small influence on RTs of Task 1 (see Strobach et al., 2015, for more information on Task 1 data and results).

In particular to explain the PRP effect, the prominent central bottleneck theory (Welford, 1952) holds that the selection of a response cannot be made for two tasks in parallel, while the initial perception stage (during which stimulus information is processed) and the final motor response stage (during which the motor response is executed) can run in parallel. Thus, response selection is conceived as a structural and unavoidable central processing bottleneck, leading to a long interruption of Task 2 processing at short vs. long SOAs and, hence, the PRP effect (Pashler, 1994). According to other bottleneck theories, a bottleneck exists in the motor response stage, preventing two responses from being initiated simultaneously or in close succession, as an alternative to the response selection bottleneck or in addition to it (e.g., De Jong, 1993; Sigman and Dehaene, 2006; Bratzke et al., 2009).

Resource theories, in contrast, assume that the critical capacitylimited stages can run in parallel, but as they share a common and limited attentional resource, this processing is less efficient compared with a single-task condition (e.g., Navon and Miller, 2002; Tombu and Jolicœur, 2003; Wickens, 2008). As was shown by Navon and Miller (2002) and Tombu and Jolicœur (2003), such capacity-sharing models can in fact explain many of the phenomena usually taken as evidence for bottleneck models. Further, if all capacity is first devoted to Task 1 and then to Task 2, the models mimic essentially a bottleneck model, which can thus be seen as a special case of capacity-sharing models.

Several studies also used variations of the PRP paradigm for analyses of executive control functions (Jiang et al., 2004; Strobach et al., 2012, 2014), for example, PRP experiments in which the order of the two tasks was not predictable (Sigman and Dehaene, 2006; Kamienkowski et al., 2011; Riuz Fernández et al., 2011; Hendrich et al., 2012; Töllner et al., 2012). The executive functions thought to be involved in performing such tasks are conceived as general-purpose control mechanisms that regulate the dynamics of human cognition and action (Miyake et al., 2000; Miyake and Friedman, 2012). In the context of dualtasks, such control mechanisms coordinate the processing of two simultaneous task streams and the access to capacity-limited processing stages (e.g., De Jong, 1995; Luria and Meiran, 2003; Sigman and Dehaene, 2006; Szameitat et al., 2006). Exemplary empirical evidence for the flexible access to capacity-limited stages comes from the observation of a general increase of RTs for Task 1 in PRP dual-task RTs compared to single-task RTs, which points to the implication of time-consuming coordination processes at the beginning of dual-task trials (e.g., Jiang et al., 2004). From a perspective of executive processes, dual-task performance data may thus point to a set of well-identifiable task coordination processes. Recent studies investigated, for example, the impact of practice (e.g., Strochbach and Schubert, 2017), age (e.g., Maquestiaux, 2016), compatibility of stimulus and response information (e.g., Hazeltine et al., 2006), or recently experienced conflict (e.g., Janczyk, 2016) on dual-task performance and executive functioning in dual-tasks. In the following section, we provide a brief overview on papers of the present research topic aiming to contribute to the further specification of executive functions implicated in dual-tasking.

#### **DUAL-TASK STUDIES IN THE PRESENT** RESEARCH TOPIC

Hommel et al. investigated the impact of binaural beats on cognitive flexibility to control two simultaneous tasks with overlapping task information in the PRP paradigm. Their findings showed that binaural beats can modulate the flexibility of executive control functions in dual-tasks. Thus, this method has the potential to bias the executive control style in dualtasks. Schubert et al. investigated the contribution of dualtask coordination skills to a reduction of dual-task costs as a result of practice. The authors showed that these skills are fully independent from practice situations and are transferable to new dual-tasks. Pieczykolan and Huestegge investigated whether flexible control of dual responses varies depending on task complexity, manipulated as the number of task-relevant response combinations and the to-be-retrieved S-R translation rules. Their findings showed that the increase of both, response combination and the S-R translation rules as well as their preparation yielded an increase of dual-task costs. In sum, the findings stress the importance of memory retrieval processes in dual-response control.

From an aging perspective, it is known that older adults are particularly impaired in dual-tasks compared with single-tasks and young adults (e.g., Verhaeghen et al., 2003; Verhaeghen, 2011). Therefore, it is relevant to investigate why older adults are impaired in dual-task situations and whether they are particularly impaired in these situations' executive control functions. In a real-world task setting, Stelzel et al. investigated the characteristics of this impairment with a specific focus on the compatibility of input and output modality pairings in the two tasks. They demonstrated that dual-task postural control is impaired in older adults in contrast to young adults particularly

<sup>&</sup>lt;sup>1</sup>To avoid confounds with, for example, how many S-R translations need to be maintained in working memory, a third condition is sometimes employed where in each trial only one stimulus is presented, but potentially stimuli from both tasks can occur within one block (so called mixed blocks or heterogeneous single-task blocks; e.g., Schumacher et al., 2001; Strobach et al., 2014; Janczyk et al., 2015).

with incompatible input-output modality pairings. A real-world task was also applied by Steinborn and Huestegge who combined mental arithmetic and phone conversation in a continuous dual-task paradigm. In the context of their attentional-failure account, they showed that mental arithmetic affected different aspects of phone conversation: information processing in participants' conversation was particularly slowed down for controlled processing components in comparison to automatic components. de Tomasso et al. analyzed electroencephalic and electromyographic responses in a passive auditory oddball paradigm for both patients with Huntington's Disease and healthy controls. A similar increase in the amplitude of the P3 component was observed for both groups when auditory stimulation was presented in dual-task situations with walking. Finally, Xing and Sun applied a dual-task situation to characterize rule-based category learning. These authors showed that the effectiveness of this type of learning is mainly affected by the load of visuospatial information on working memory in a dual-task context. Thus, this dual-task study potentially informs about the structure of the working memory component that coordinates dual-tasking.

### TASK SWITCHING PARADIGMS, THEORIES, AND EXECUTIVE **FUNCTIONING**

Task switching refers to a multitasking situation where two or more tasks are presented sequentially without temporal overlap (e.g., Monsell, 2003; Kiesel et al., 2010). Contrasting with most of the studies on dual-tasking, the stimuli presented in task switching situations afford not only the currently relevant task but also the other task(s). For instance, participants may be presented with colored shapes as stimuli and frequently alternate between judging the color (Task A) or the shape (Task B). Another frequently used experimental protocol requires switching between purely semantic tasks, such as when participants judge the magnitude (Task A) vs. the parity (Task B) of stimulus digits. In single-task blocks, either Task A or Task B is presented exclusively. In mixed blocks, participants are confronted with both tasks either in a pre-specified task sequence such as AABBAABB (i.e., alternating runs paradigm; Rogers and Monsell, 1995) or with a random task sequence and a task cue that precedes or accompanies stimulus presentation (i.e., task cueing paradigm; Meiran, 1996). In these mixed blocks, the tasks can either repeat from one trial to the next (i.e., task repetitions) or switch (i.e., task switches), and two types of performance costs can be assessed. First, mixing costs are defined as the difference between the mean performance in trials with task repetitions in mixed blocks and the mean performance in single-task blocks (Koch et al., 2005; Rubin and Meiran, 2005). Second, switch costs are defined as the difference between the performance in task switch trials and the performance in task repetition trials within the mixed blocks (Rogers and Monsell, 1995).

The most prominent theoretical issue in task switching research has been the question of the origin of switch costs, particularly of so-called residual switch costs that are consistently found even after long preparation intervals during which participants have foreknowledge about the identity of the upcoming task. Although some accounts attribute residual switch costs to the duration of an executive process of task-set reconfiguration, occurring after encoding of the task stimulus (Rogers and Monsell, 1995; Rubinstein et al., 2001), there seems to be broad consensus that at least part of residual switch costs reflect priming from previous execution of the other task (e.g., Allport et al., 1994). In this regard, particular interest has been devoted to the role of task-set inhibition. Although the precise role of task-set inhibition concerning the residual switch costs is still unclear, convincing evidence for task-set inhibition is seen in the N-2 task repetition effect (a.k.a. the backward inhibition effect), found in task switching protocols that involve three different tasks (i.e., Tasks A, B, and C). The N-2 task repetition effect refers to the finding that the final trial of an ABA task sequence tends to be associated with slower responses than the final trial of a CBA sequence (Mayr and Keele, 2000), as would be expected if performance suffered from inhibition of the task-set for Task A in the former but not (or less so) in the latter case. Another major point in the task switching literature refers to attempts of specifying the processes involved in task preparation. Effective task preparation has been inferred from findings of improved performance when the preparation interval that precedes the presentation of the imperative stimulus is increased (Rogers and Monsell, 1995; Meiran, 1996). The precise processes involved in task preparation have proved difficult to determine, however (overviews in Karayanidis et al., 2010; Kiesel et al., 2010). More recent developments in task switching research refer to effects of task switching practice (e.g., Minear and Shah, 2008), individual differences (e.g., von Bastian and Druey, 2017), or the comparison of voluntary task selection with instructional task cuing (e.g., Arrington and Logan, 2004).

#### TASK SWITCHING STUDIES IN THE PRESENT RESEARCH TOPIC

Articles included in the present research topic contribute to our understanding concerning the classical questions of task-set inhibition and task preparation as well as concerning practice, age-related differences, and voluntary task selection. As regards task-set inhibition, Schuch, using a diffusion model analysis, specified that older adults are not generally impaired in task inhibition in comparison to younger adults. Alternatively, there are age differences in dealing with task inhibition as reflected by differences in the speed-accuracy trade-off between these age groups. Jost et al. investigated whether task dominance determines backward inhibition. The results of their study showed that inhibition was stronger for more dominant tasks, suggesting that the amount of inhibition is adjusted in a contextsensitive manner. Concerning task preparation, Kleinsorge and Scheil presented redundant pre-cues that constrain the number of possible tasks from four to two before the task was cued unambiguously (replicating previous findings of an advantage of such pre-cuing; Kleinsorge and Scheil, 2015) and analyzed

spontaneous eye blink rates. Changes in the eye blink rate during the initial part of the experimental session were correlated with pre-cuing benefit. Distinguishing between the preparation of perceptual and non-perceptual task processes, Wendt et al. focused on situations in which tasks differed regarding their perceptual demands of stimulus selection. Intermixing trials of a probe task they found evidence for preparatory adoption of task-specific attentional sets, that is, for focusing or defocusing of visual attention depending on the stimulus selection demands of a likely upcoming task. Wendt et al., by contrast, investigated preparation in the absence of a difference in perceptual demands between tasks. Analyzing task switching performance across six consecutive sessions, they extended previous evidence suggesting that task switching practice results in a speed-up of the preparation to non-perceptual preparatory processes. This study also introduced a probe task method-similar to the one applied by Wendt et al.—to research on task switching practice.

Buttelmann and Karbach's as well as Kray and Fehér's focus of interest is on age-related effects on task switching practice. Buttelmann and Karbach review the findings of training interventions and transfer in early and middle childhood, revealing substantial plasticity for different aspects of cognitive flexibility. Kray and Fehér assess the transferability of improved task switching performance after practice in young and older adults. Their findings suggest that the requirement to resolve interference between tasks is critical for the occurrence of transfer particularly in the elderly. A comparison of voluntary and instructed task selection—concerning the impact of taskspecific action effects—was made by Sommer and Lukas. Finally, Moon et al. investigated interruptions of a visuo-tactile task by a second task that also involved visual and haptic stimuli, providing evidence for a helpful role of redundant haptic information in reducing the cost of interruption.

#### **SUMMARY**

In sum, the present research topic combines recent research in dual-tasks and task switching, focusing on the impact of executive functioning in these types of multitasking situations. In addition to the specific research issues addressed by the individual contributions, this collection of studies nicely shows the diversity of theoretical questions and methodological approaches in contemporary cognitive-neuroscientific research in this area.

#### AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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# Age-Related Interference between the Selection of Input-Output Modality Mappings and Postural Control—a Pilot Study

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Age-related decline in executive functions and postural control due to degenerative processes in the central nervous system have been related to increased fall-risk in old age. Many studies have shown cognitive-postural dual-task interference in old adults, but research on the role of specific executive functions in this context has just begun. In this study, we addressed the question whether postural control is impaired depending on the coordination of concurrent response-selection processes related to the compatibility of input and output modality mappings as compared to impairments related to working-memory load in the comparison of cognitive dual and single tasks. Specifically, we measured total center of pressure (CoP) displacements in healthy female participants aged 19-30 and 66-84 years while they performed different versions of a spatial one-back working memory task during semi-tandem stance on an unstable surface (i.e., balance pad) while standing on a force plate. The specific working-memory tasks comprised: (i) modality compatible single tasks (i.e., visual-manual or auditory-vocal tasks), (ii) modality compatible dual tasks (i.e., visual-manual and auditory-vocal tasks), (iii) modality incompatible single tasks (i.e., visual-vocal or auditory-manual tasks), and (iv) modality incompatible dual tasks (i.e., visual-vocal and auditory-manual tasks). In addition, participants performed the same tasks while sitting. As expected from previous research, old adults showed generally impaired performance under high working-memory load (i.e., dual vs. single one-back task). In addition, modality compatibility affected one-back performance in dual-task but not in single-task conditions with strikingly pronounced impairments in old adults. Notably, the modality incompatible dual task also resulted in a selective increase in total CoP displacements compared to the modality compatible dual task in the old but not in the young participants. These results suggest that in addition to effects of working-memory load, processes related to simultaneously overcoming special linkages between input- and output modalities interfere with postural control in old but not in young female adults. Our preliminary data provide further evidence for the involvement of cognitive control processes in postural tasks.

Keywords: cognitive-postural dual task, postural stability, working memory, modality compatibility, aging

#### INTRODUCTION

The risk of falls is significantly higher in old compared to young adults and fall-related injuries severely threaten old adults' quality of life (Tideiksaar, 1996). Adequate levels of postural control are crucial for the successful performance of activities of daily living and to avoid falls. In everyday life, however, postural tasks are rarely performed in isolation but usually combined with cognitive activities. Age-related decline in performing such combined cognitive-postural activities, i.e., the concurrent performance of a postural and a cognitive task has also been related to an increased fall-risk in old age (Bergland and Wyller, 2004; Lajoie and Gallagher, 2004; Boisgontier et al., 2013). This cognitive-motor dual-task decline in performance might be related to age-related decrements in (i) postural stability per se (Granacher et al., 2011), (ii) working memory capacity (Sander et al., 2012; Heinzel et al., 2014), or (iii) specific executive functions involved in coordinating concurrent task performance (Walshe et al., 2015). Here, we directly compared age-related effects on (i) cognitive and postural single tasks (ii) cognitive-postural tasks with different working-memory load (cognitive single vs. cognitive dual task), and (iii) cognitivepostural tasks requiring specific executive functions involved in the coordination of concurrent response-selection processes to different degrees.

Postural control involves controlling the body's position in space for the dual purposes of stability and orientation (Shumway-Cook and Woollacott, 2007). The alignment of posture is not just a passive state but requires the processing and integration of multiple information streams, e.g., proprioceptive, cutaneous, visual, and vestibular sensory processing (Peterka, 2002). Accordingly, postural stabilization involves the recruitment of lower level peripheral factors on the brainstem level (Honeycutt et al., 2009) as well as higher (central) level control involving cortical and direct cortico-spinal processing (Taube et al., 2008; Taubert et al., 2010). More specifically, the regulation of posture has been related to cerebellar-cortical and fronto-striatal interactions (Jacobs and Horak, 2007; Mihara et al., 2008). In addition, functional imaging studies further support the activation of basal ganglia when imagining upright stance (Jahn et al., 2004). Studies on postural control in old age indicate that supraspinal contributions become more important as people age (Baudry, 2016), thus providing a greater potential for interference with cognitive tasks due to overlapping cortical recruitment (Herath et al., 2001). Note however, that the identification of the specific cortical sub-regions involved in postural control is still rather vague as actual postural control tasks cannot be directly performed in high-resolution functional imaging environments.

Alternatively, cognitive-postural dual-task designs can be applied to investigate, which cognitive tasks actually interfere with postural control. This, in turn, gives us direct evidence about the psychological mechanisms interfering with postural control and indirect evidence about the underlying cortical contributions to postural control.

From a psychological perspective, the dominant view holds that more attentional resources are dedicated to postural control

in old age, which in turn interferes with attentionally demanding cognitive tasks (Huxhold et al., 2006; Rapp et al., 2006; Doumas et al., 2008; Berger and Bernard-Demanze, 2011; Granacher et al., 2011). In line with this, limited attentional resources have been shown to also predict falls in older individuals (Woollacott and Shumway-Cook, 2002). According to this view, more demanding postural tasks should generally lead to more interference with resource-demanding cognitive tasks in old age and vice versa (Woollacott and Shumway-Cook, 2002; Fraizer and Mitra, 2008; Boisgontier et al., 2013).

In contrast to this "limited resource hypothesis" (Kahneman, 1973; Wickens, 1980), specific cognitive control processes might affect the performance of a cognitive-postural dual task. Several dual-task models assume that executive control is crucial for the coordination of two temporally overlapping tasks (Meyer and Kieras, 1997; Logan and Gordon, 2001; Sigman and Dehaene, 2008). In fact, functional imaging studies provide converging evidence for this view by showing that lateral prefrontal activity is associated with specific aspects of dual-task coordination (D'Esposito et al., 1995; Szameitat et al., 2002; Schubert and Szameitat, 2003; Stelzel et al., 2008, 2009). The coordination demands associated with the concurrent performance of two cognitive tasks can be assumed to depend on different factors, such as the degree of structural or temporal overlap between the tasks (Sigman and Dehaene, 2008).

Here, we examined the effects of input-output modality compatibility, a factor, which has previously been shown to dramatically increase cognitive dual-task interference while keeping structural overlap at a minimum (Hazeltine et al., 2006; Stelzel et al., 2006; Stephan and Koch, 2010; Stelzel and Schubert, 2011). Modality compatibility refers to the similarity of stimulus modality and the modality of response-related sensory consequences, a principle based on ideomotor theory (Greenwald and Shulman, 1973; Prinz, 1990; Hommel et al., 2002). According to this view, preferred processing is assumed for stimulus-response-mappings with such a similarity between the stimulus modality and the sensory consequences of the response. Accordingly, special linkages are assumed for auditory-vocal and visual-manual tasks (modality compatible), but not for auditory-manual and visual-vocal tasks (modality incompatible). The latter tasks might require controlled translation from the stimulus information to the response to a higher degree (Kornblum et al., 1990), similar to overcoming prepotent response tendencies in the Stroop task. Empirical evidence for these additional processing demands stem from studies using temporally overlapping dual-task designs (Hazeltine et al., 2006; Stelzel et al., 2006; Stelzel and Schubert, 2011) and sequential task-switching designs (Stephan and Koch, 2010, 2011), combining either two modality compatible or two modality incompatible tasks. In the both contexts, averaging across the two component tasks eliminates effects of inputand output modality, pinpointing differences to interference of central translation processes and their coordination. These studies show strong increases in dual-task and task-switching costs in modality incompatible compared to modality compatible overlapping tasks, while single tasks do not differ depending on input-output modality compatibility. This suggests that

the translation of stimulus information to a response in a non-preferred output modality is a capacity-limited process, which requires active coordination between tasks to a higher degree (Meyer and Kieras, 1997; Logan and Gordon, 2001; Sigman and Dehaene, 2008). This dual-task-specific effect of modality compatibility was further accompanied by increased dual-task-related activity in the left lateral frontal cortex (Stelzel et al., 2006), further suggesting that coordinating the responseselection processes of the two tasks becomes more demanding for modality incompatible mappings. Thus, the manipulation of input-output modality compatibility in a dual-task context provides a unique option to examine executive processes in dual-task coordination while keeping structural (input-/ output-) overlap and differences in working memory load at a minimum.

Importantly, aging has been shown to affect functions associated with anterior brain regions more than those associated with posterior regions (Brehmer et al., 2011; Grady, 2012; Heinzel et al., 2014, 2016). Consequently, deficits in cognitivecognitive dual tasks in old adults have been interpreted as a decline in executive functions in several studies (Hein and Schubert, 2004; Clapp et al., 2011). This implies that old adults may show decrements in performing cognitive-cognitive dual tasks involving modality incompatible mappings as these are assumed to require executive functions and associated frontal brain regions to a higher degree.

Whether or not such specific dual-task coordination demands related to modality compatibility also interfere with postural stability is not known yet. We tested this by measuring center of pressure (CoP) displacements in young and old female participants aged 19-30 and 66-84 years, respectively while they performed different versions of a spatial one-back working memory task during semi-tandem stance on an unstable surface (i.e., balance pad) while standing on a force plate. Both groups also performed the same tasks while sitting.

In accordance with the limited resource hypothesis, we expected pronounced effects of working memory load (cognitive dual task vs. single task) on cognitive-postural task performance in old age. In addition, we hypothesized specific age-related effects of executive control (input-output modality compatibility) when two cognitive tasks are performed simultaneously with a postural task. Most importantly, we expected these effects to be reflected in increased total CoP displacements in the old but not the young adults.

#### MATERIALS AND METHODS

#### **Participants**

Eleven old women aged 66-84 years and 15 young women aged 19-30 years participated in this study. Senior participants were recruited via two health and rehabilitation sports clubs while young adults were mainly recruited through student mailing lists at the University of Potsdam, Germany. All participants were in healthy condition with no signs of neurological or psychiatric disorders, no hearing impairments, normal or corrected-tonormal vision, and no fall-incidents over the last 12 months prior to the start of this study. Furthermore, inclusion criteria for young women were suitability for measurement with magnetic resonance imaging (MRI), as they participated in a functional MRI study in a separate session. These data will be reported elsewhere. See Table 1 for demographic and neuropsychological data of the participants of the two age groups.

This study was designed according to the Declaration of Helsinki and was approved by the local ethics committee of the University of Potsdam, Germany. Before the start of the study, participants were informed and signed written informed consent. Study participation was reimbursed monetarily with 7.5 € per test hour.

#### **Cognitive and Postural Tasks**

Participants performed cognitive single tasks or cognitive dual tasks either with hardly any postural demands during sitting or with additional postural demands during the semi-tandem stance on an unstable surface (i.e., balance pad). In all conditions, the cognitive task included a spatial one-back task (cognitive single or cognitive dual task), which comprised either modality compatible or modality incompatible input-output modality pairings (see Figure 1A). In addition, participants also completed a postural single task without a concurrent cognitive task (visual fixation). Table 2 provides an overview of all tasks and task combinations, which will be explained in more detail below. In all tasks, participants were instructed to keep their eyes opened with the head and eyes directed toward a monitor that was individually adjusted to the respective body height of the participant. Throughout testing, participants wore headphones with an attached microphone. In addition, all participants carried a single response key in their right hand, which allowed them to press a button with their right thumb.

#### Postural Single Tasks (P)

With their arms hanging loose to the sides of the body, participants were instructed to stand in semi-tandem stance on

TABLE 1 | Demographic and neuropsychological data of young and old adults (means and standard deviations).

	GROUPS		
	Young participants $(n = 15)$	Old participants (n = 11)	
Age (years)	24.8 (3.6)	72.9 (4.1)	
Years of education	16.8 (3.0)	14.7 (3.7)	
Trail making test—A (seconds)	23.3 (5.9)	32.6 (6.6)	
Trail making test—B (seconds)	48.3 (13.4)	90.1 (26.0)	
Digit symbol test (number of correct matches in 90 s)	68.9 (11.6)	49.4 (8.9)	
Leistungspruefsystem (LPS)—subtest 3, number of correct symbols	31.1 (3.8)	20.9 (3.9)	
Multiple choice vocabulary test (Mehrfachwortschatztest, MWT), number of correct words	30.9 (2.6)	33.2 (1.5)	
Digit span forward	7.0 (1.1)	6.6 (1.0)	
Digit span backward	5.8 (1.1)	4.8 (1.7)	
Mini mental state examination (points)	Not assessed	29.2 (0.9)	
Hand grip strength (kg)	28.2 (5.2)	21.9 (4.9)	

#### **A Component Tasks B** Experimental Procedure Modality compatible tasks Session: modality compatible visual-manual task Posture CP<sub>av</sub> CCP<sub>vm-av</sub> Stand I p<sub>dynamic fix</sub> CPvm P<sub>dynamic fix</sub> P<sub>stable fix</sub> CC<sub>vm-av</sub> Sit I C<sub>vm</sub> Cav CCP<sub>vm-av</sub> Stand II CP<sub>av</sub> CP<sub>vm</sub> P<sub>dynamic fix</sub> P<sub>dynamic fix</sub> P<sub>stable fix</sub> auditory-vocal task CC<sub>vm-av</sub> Sit II C... Cvn Stand III CCP<sub>vm-av</sub> CP<sub>vm</sub> CP<sub>av</sub> P<sub>dynamic fix</sub> P<sub>dynamic fix</sub> P<sub>stable fix</sub> Sit III CC<sub>vm-av</sub> Cav C<sub>vm</sub> Session: modality incompatible Modality incompatible tasks Posture CP<sub>vv</sub> CP<sub>am</sub> visual-vocal task Stand I P<sub>stable fix</sub> P<sub>dynamic fix</sub> CCP<sub>vv-am</sub> P<sub>dynamic fix</sub> P<sub>stable fix</sub> CC<sub>vv-am</sub> Sit I Cam CP<sub>am</sub> CCP<sub>vv-am</sub> CP,, Stand II P<sub>dynamic fix</sub> P<sub>stable fix</sub> P<sub>dynamic fix</sub> CC<sub>vv-an</sub> Sit II $C_{am}$ C... CP<sub>am</sub> CCP<sub>vv-an</sub> CPvv Stand III P<sub>stable fix</sub> P<sub>dynamic fix</sub> P<sub>dynamic fix</sub> auditory-manual task CC<sub>vv-am</sub> Sit III

**FIGURE 1 | Task design. (A)** Types of modality compatible and modality incompatible component one-back working memory tasks. Visual displays consisted of 6 possible stimulus locations, 3 to the left and 3 to the right of the fixation cross. Auditory stimuli were 3 tons of different frequencies, presented either to the left or to the right ear. Participants responded to one-back targets via button press in the manual conditions or by saying "yes" in the vocal conditions. **(B)** Study design. Each session included six runs with three standing conditions alternating with three sitting conditions. Presentation order of task blocks is shown from left to right. Each run in standing posture included seven task blocks and each run in sitting posture three task blocks each.  $P_{stablefix}$ , single postural task with stable fixation;  $P_{dynamicfix}$ , single postural task with dynamic fixation; vm, visual-manual task; av, auditory-vocal task; vv, visual-vocal task; am, auditory-manual task; for all other abbreviations please refer to **Table 2**.

TABLE 2 | Overview of task conditions and abbreviations.

	Postural task	Cognitive single task	Cognitive dual task
SIT	x	C (cognitive single task)	CC (cognitive-cognitive dual task)
STAND	P (postural single task)	CP (cognitive-postural dual task)	CCP (cognitive- cognitive-postural triple task)

an unstable surface (i.e., balance pad) with the dominant leg posterior to the non-dominant leg. To determine participants' dominant leg we asked them to softly kick a ball placed approximately 1.5 m right in front of the participant. We registered the kicking leg as dominant leg. Further, participants answered two questions of the lateral preference inventory (Coren, 1993) concerning which leg they usually use when they a) want to pick something from the ground and b) should put out a cigarette on the ground. We defined the dominant leg as the leg, which was the most mentioned or used, respectively, in these three situations. The balance pad was placed on a

one-dimensional force plate (Leonardo 105 Mechanograph®; Novotec Medical GmbH Pforzheim, Germany) so that total CoP were recorded during testing. Participants had to keep their head straight and their gaze fixed either on a stable visual stimulus (stable fixation condition) or on a dynamic visual stimulus (dynamic fixation condition). In the stable fixation condition, participants had to focus their gaze on a fixation cross which was presented in the center of the monitor screen. In the dynamic fixation condition, a fixation cross and an ampersand symbol ("&," fontsize: 54) were displayed alternately in the center of the screen, with presentation times matched to presentation times in the cognitive tasks (i.e., 500 ms ampersand, 1,500 ms fixation). Here, we only report the dynamic fixation condition, as our pilot studies revealed higher postural instability during stable fixation.

#### Cognitive Single Tasks (C)

Participants performed different versions of a spatial one-back working memory task while sitting, i.e., with hardly any postural demands. Input stimuli were either visual or auditory and responses were given either manually or vocally. The stimulus duration was 500 ms followed by a fixation inter-stimlus interval

of 1,500 ms. Task blocks consisted of 16 trials, including 5 one-back targets and 11 non-targets in pseudo-random order. According to modality compatible (i.e., visual-manual and auditory-vocal) or modality incompatible (i.e., visual-vocal and auditory-manual) input-output modality pairings, there were four different types of cognitive single tasks (see **Figure 1A**):

#### Modality compatible visual-manual single task

The target display consisted of a black background with a white fixation cross in the center. Visual stimuli were white squares which were presented at six different locations (up, center, down), three on each side of the fixation cross. Participants were instructed to respond fast and correct via button press when the position of the current square was the same as in the preceding trial.

#### Modality compatible auditory-vocal single task

Three different tones (200, 450, 900 Hz) were presented via headphones while a static fixation cross was displayed on the screen. The tones were presented either to the left or the right ear, resulting in 6 different stimuli. As in the visual task, participants were instructed to respond fast and correctly, when the same tone was presented to the same ear in trials n and n-1. Participants were instructed to respond vocally to target stimuli by saying "yes" (German: "Ja").

#### Modality incompatible visual-vocal single task

The target display and stimulus presentation were the same as in the visual-manual single task, but in this case participants had to respond to target stimuli vocally by saying "yes" (German: "Ja").

#### Modality incompatible auditory-manual single task

Targets and stimulus presentation were the same as in the auditory-vocal condition, but here participants had to respond to target stimuli manually via button press.

#### Cognitive-Cognitive Dual Tasks (CC)

Participants performed two cognitive tasks simultaneously while sitting on a chair with a backrest. For this, a visual and an auditory stimulus were presented simultaneously for 500 ms, followed by a 1,500 ms inter-stimulus interval. Participants were instructed to decide for both stimulus modalities whether or not the stimulus was identical to the stimulus in the trial before (dual one-back task). Per task block five one-back targets were presented, i.e., two or three in the visual modality and two or three in the auditory modality. One-back targets were presented either in the auditory or in the visual modality but never simultaneously.

Both concurrent tasks were either modality compatible or modality incompatible.

#### Modality compatible dual task

Participants performed the visual-manual and the auditory-vocal task simultaneously.

#### Modality incompatible dual task

Participants performed the visual-vocal and the auditory-manual task simultaneously.

#### Cognitive-Postural Dual Task (CP)

Participants performed the postural task (P) while simultaneously performing one of the four cognitive single tasks (C) as outlined above, i.e., either with modality compatible or modality incompatible input-output modality pairings.

#### Cognitive-Cognitive-Postural Triple Tasks (CCP)

Participants performed the postural task (P) while simultaneously performing one of the two cognitive-cognitive dual tasks (CC), i.e., either the modality compatible or the modality incompatible dual task.

## **Performance Assessment**

#### Postural Control

Postural control was assessed during semi-tandem stance (barefoot or with socks) on an unstable surface (i.e., balance pad) with the dominant leg posterior to the non-dominant leg. The balance pad (Airex<sup>®</sup>) was placed on a one dimensional force plate. Total CoP displacements (mm) were computed using CoP displacements in medio-lateral and anterior-posterior directions by means of the Pythagorean theorem. Assessment duration (33 s) was chosen in order to optimize reliability of postural stability measurement (LeClair and Riach, 1996) and in accordance with the cognitive task requirements.

#### Cognitive Performance

Cognitive task stimuli were presented and manual and vocal responses were recorded via Presentation software (https://www.neurobs.com/).

#### **Procedure**

We chose a within-subjects design and kept task and trial order the same across subjects (see **Figure 1B**) to allow for individual differences analyses of training effects, as this experimental protocol will be applied to examine the effects of a specific balance training in the near future.

Participants came to the biomechanics laboratory of the Division of Training and Movement Sciences, University of Potsdam for two test occasions. Test dates were separated by at least 1 week or by 4 weeks maximum. The first date comprised a neuropsychological screening procedure, including tests for vision and hearing abilities, general cognitive functioning (e.g., Mini Mental State Examination Test for seniors) and several specific neuropsychological tests (e.g., Digit Span, Trail Making A and B, see **Table 1**). At the end of the date, participants practiced two blocks of 32 trials for each cognitive single task and 4 blocks of 32 trials for each cognitive dual task after detailed instructions.

At the second date, participants processed the experimental tasks as outlined above while total CoP displacements and electroencephalographic (EEG) data were recorded using a mobile 64-channel EEG system. The young participants additionally participated in a functional MRI study at a third date. Further details of the neuropsychological measures, the EEG, and the fMRI data will be reported elsewhere. Here, we focus on the cognitive and CoP data, which were recorded at the second date.

The experiment during the second date consisted of two separate sessions (see Figure 1B), with six runs each. Within each run, three cognitive task blocks were performed (two cognitive single tasks, one cognitive dual task). In each session, three runs were performed in standing posture and three while sitting upright, presented in an alternating mode. Within one session, all tasks were either modality compatible or modality incompatible, respectively. The clustering of tasks into one session, which included only modality compatible tasks and into another session, which included only modality incompatible task was conducted to achieve a better level of general task performance, which might be impaired in a situation with permanent switches between these task sets. All participants performed both sessions in direct succession with a short break in-between. The test session order (modality compatible-modality incompatible vs. modality incompatible—modality compatible) was randomly assigned to participants such that half of the participants started with modality compatible tasks and half of the participants started with modality incompatible tasks.

All participants started in the semi-tandem stance condition. The standing condition always began with one stable fixation block, followed by a dynamic fixation block (33 s each to match the duration of the cognitive tasks). Thereafter, the three cognitive task trials followed (two cognitive single tasks and one cognitive-cognitive dual task, order counterbalanced across runs, 33 s each), which were again followed by one dynamic fixation block and one static fixation block. Each cognitive task block included 16 trials. While sitting, only the three cognitive task blocks were performed in the same order as in the previous standing condition.

Participants practiced the relevant tasks (modality compatible/modality incompatible) once more at this second date right before the corresponding (modality compatible/modality incompatible) experimental session in the sitting condition (one task block per cognitive single task, two task blocks per cognitive dual task).

#### Statistical Analyses

Performance data of the cognitive tasks were calculated as p(Hit)p(False alarms). Vocal and manual responses were recorded during the experiment for the period of each one-back trial duration (2 s). Vocal data were analyzed offline with a selfdeveloped Matlab tool (MathWorks; Natick, MA). The custommade tool (Reisner and Hinrichs, 2016) was developed to facilitate automated identification of trials with correct vocal responses and to extract reaction time latencies based on simple signal amplitude measurement. The tool was validated successfully via manual coding of vocal responses (Cohens Kappa = 0.941, p = 0.000). Due to technical failure during recording, the vocal data of five young participants were not recorded properly and could not be analyzed. These participants were excluded from all analyses including one-back performance data. Cognitive performance data were averaged for both component tasks of each modality compatibility condition, resulting in four performance measures for the modality compatible and modality incompatible condition, respectively (C, CP, CC, CCP). These data were then subjected to a mixed general linear model, with 3 within subject factors with two levels each: 1. sit vs. stance  $\times$  2. cognitive single vs. cognitive dual task  $\times$  3. modality compatible vs. modality incompatible, and 4. age group as between subject factor. In addition to these performance measures, mean reaction times for correct target responses are reported.

As for the postural control data, we ran an exploratory data analysis using JMP® software (JMP® 8, SAS Institute GmbH, Germany) to exclude outlier blocks for each participant. Using IMP software, outlier blocks were identified by box plot analyses on the subject level and defined as blocks which were outside the whiskers, that is trials that were outside the range of <1st quartile  $-1.5^*$ interquartile-range or >3rd quartile + 1.5\*interquartile range.

Table 3 shows the average number of task blocks per condition and group included in the final data set (n = 15)young participants, n = 10 old participants). Performance data of total CoP displacements for the single postural task (P), cognitive-postural dual task (CP), and cognitivecognitive-postural triple task (CCP) for modality compatible and incompatible mappings were calculated by averaging CoP displacements of respective conditions. Relative multiple task costs for total CoP-displacements were calculated for each run and averaged per condition (i.e., modality compatible vs. incompatible mappings) according to the formula of Doumas et al. (2008). Thus, relative dual-task costs of total CoP displacements concerning the difference between CP and P were calculated as DTCp = (CP-P)/P) \* 100, whereas triple-task costs of total CoP displacements concerning the difference between CCP and P were calculated as TTCp = ([CCP-P]/P) \* 100.

To examine assumed effects of task condition and modality compatibility, we ran a 2 (CP vs. CCP)  $\times$  2 (modality compatible vs. modality incompatible) repeated measures ANOVA with age group as between subject factor (old vs. young). For further analyses, we used planned t-test to elucidate which conditions drive reported significant effects. All statistical analyses were processed using IBM SPSS Statistics, Version 22.0. Effect sizes  $(\eta^2_{p_1})$  d) are reported for all analyses to characterize the effectiveness of the experimental factors.

In order to directly compare trade-off effects between cognitive and postural performance, we also calculated relative

TABLE 3 | Means and standard errors in parentheses for number of task blocks per participant per condition and group included in analysis of total center of pressure (CoP)-displacements.

	GROUP			
	Young participants (n = 15) Old Participants (n			
COMPATIBL	E SESSION			
P-Task	5.73 (0.15)	5.82 (0.12)		
CP-Task	5.50 (0.16)	5.73 (0.20)		
CCP-Task	2.93 (0.07)	2.64 (0.20)		
INCOMPATI	BLE SESSION			
P-Task	5.80 (0.11)	5.91 (0.09)		
CP-Task	5.87 (0.09)	6.00 (0.00)		
CCP-Task	2.93 (0.07)	2.91 (0.09)		

P, Postural Single Task; CP, Cognitive-Postural Dual Task, CCP, Cognitive-Cognitive-Postural Triple Task.

dual-task costs for cognitive performance data in the cognitive single and the cognitive dual-task condition according to the formulae:  $DTC_{CP} = ([C-CP]/C) * 100$  and  $DTC_{CCP}$ = ([CC-CCP]/CC)\*100. These variables as well as the corresponding variables from the postural control data were then z-standardized and entered into one common repeated measures ANOVA, now including the factor performance domain (cognition vs. posture) in addition.

#### **RESULTS**

#### **Cognitive Task Performance**

The results of the 2 (sit vs. stance, within)  $\times$  2 (cognitive single vs. dual task, within) × 2 (modality compatible vs. modality incompatible, within) × 2 (young vs. old, between) ANOVA revealed a cognitive performance pattern consistent with (1) previous findings of selective modality compatibility effects (i.e., performance decrements for modality incompatible compared to modality compatible tasks) on cognitive dual as compared to cognitive single tasks in both age groups, (2) expected pronounced effects of working memory load (cognitive single vs. cognitive dual task) for old compared to young participants during semi-tandem stance (3) expected pronounced effects of modality compatibility for old compared to young participants during semi-tandem stance. For an overview of all cognitive performance means and reaction times per condition see Table 4 and Figure 2, for statistical results, Table 5. Note that statistical analyses are only reported for the p(Hit)-p (False Alarm) measure, which reflects performance in target and non-target trials likewise.

#### Age-Independent Task Effects

Working-memory performance in the whole group was higher for modality compatible (Mean (M) = 0.87; Standard Error

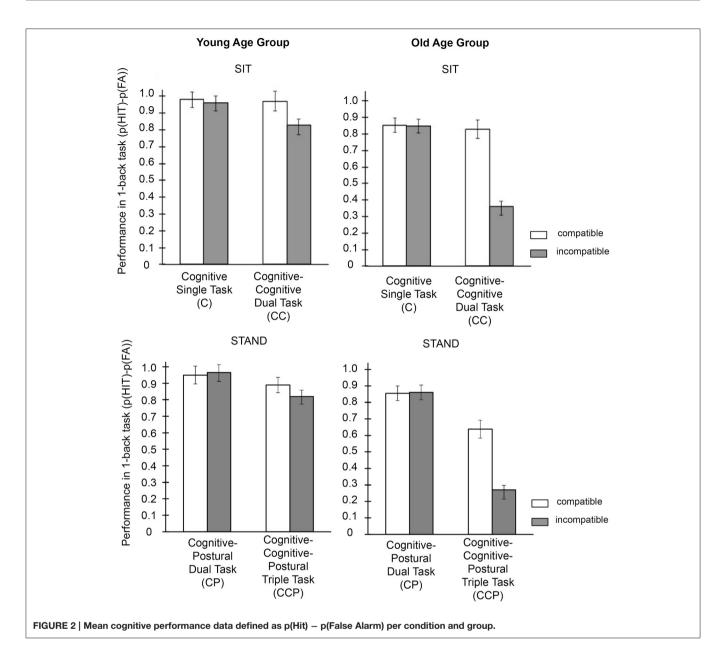
(SE) = 0.03) compared to modality incompatible tasks (M = 0.74; SE = 0.03), for cognitive single tasks (M = 0.91; SE = 0.03) compared to cognitive dual tasks (M = 0.70; SE = 0.02) and for sitting (M = 0.83; SE = 0.02) compared to standing (M = 0.78; SE = 0.03). As expected, modality compatibility effects were completely triggered by the cognitive-cognitive dualtask condition (difference between cognitive dual tasks: M =0.27; SE = 0.04) and not present in the cognitive single-task condition [difference between cognitive single tasks: M = 0.001; SE = 0.01; comparison of compatibility effects between cognitive single tasks and cognitive dual tasks,  $t_{(20)} = 6.0$ , p < 0.001, Cohen's d = 1.79], thus reflecting increased interference effects associated with modality compatibility. Also, the additional postural task affected modality-compatibility effects, indicating higher modality compatibility effects while sitting (M = 0.16; SE = 0.03) compared to standing [M = 0.11; SE = 0.03; comparison of compatibility effects between sitting and standing,  $t_{(20)} =$ 3.0, p = 0.007, d = 0.49]. This effect did not interact with the factor cognitive single vs. cognitive dual task. Finally, the effects of cognitive single task vs. cognitive dual tasks depended on the postural control condition. In other words, cognitive dualtask effects were more pronounced while standing (difference between single and dual task: M = 0.26; SE = 0.04) compared to sitting [M = 0.17; SE = 0.04, comparison of dual-task effects between sitting and standing  $t_{(20)} = 4.23$ , p < 0.001, d = 0.47].

#### **Age-Dependent Effects**

Working-memory performance was generally worse in old (M = 0.69; SE = 0.04) compared to young participants (M = 0.92; SE = 0.04). In addition, all main effects were more pronounced in old participants: they had stronger performance decrements in cognitive dual tasks compared to single tasks [difference between dual tasks and single tasks: old: M = 0.33; SE = 0.05; young: M = 0.09; SE = 0.02; difference between age groups:

TABLE 4 | Cognitive performance data (p(Hit)-p(False Alarm)) and reaction times per condition (standard errors in parentheses).

	SIT			STAND
	Cognitive single	Cognitive dual	Cognitive-postural dual	Cognitive-cognitive - postura
	task (C)	task (CC)	task (CP)	triple task (CCP)
p(Hit)-p(FALSE ALARM)				
Young Participants ( $n = 10$ )				
Modality compatible	0.98 (0.05)	0.97 (0.04)	0.95 (0.05)	0.89 (0.05)
Modality incompatible	0.96 (0.06)	0.83 (0.03)	0.97 (0.05)	0.82 (0.04)
Old Participants (n = 11)				
Modality compatible	0.85 (0.04)	0.83 (0.04)	0.85 (0.05)	0.64 (0.05)
Modality incompatible	0.85 (0.05)	0.36 (0.03)	0.86 (0.05)	0.27 (0.04)
REACTION TIMES (ms)				
Young Participants				
Modality compatible	596.1 (41.7)	784.3 (56.4)	585.6 (46.0)	795. 4 (45.9)
Modality incompatible	602.3 (35.6)	847.9 (56.9)	606.4 (34.9)	861.5 (69.3)
Old Participants				
Modality compatible	658. 4 (35.5)	840.0 (48.1)	614.8 (39.2)	910.4 (39.2)
Modality incompatible	585.7 (30.3)	908.4 (48.6)	593.9 (29.8)	923.3 (59.1)



 $t_{(19)}=4.01,\ p<0.001,\ d=1.75],$  for modality incompatible compared to modality compatible tasks [difference between modality incompatible and modality compatible tasks; old:  $M=0.21;\ SE=0.02;$  young:  $M=0.05;\ SE=0.02;$  difference between age groups:  $t_{(19)}=4.93,\ p<0.001,\ d=2.15]$  and marginally significant higher decrements during standing compared to sitting [difference between standing and sitting: old:  $M=0.07;\ SE=0.02;$  young:  $M=0.03;\ SE=0.02;$  difference between age groups:  $t_{(19)}=1.87,\ p=0.077,\ d=0.82].$  Importantly with respect to aging effects on modality compatibility, the difference between modality compatibility effects in cognitive single tasks compared to cognitive dual tasks was even larger for old participants (difference in compatibility effects in dual tasks and single tasks:  $M=0.42;\ SE=0.05)$  compared to young adults  $(M=0.10;\ SE=0.02;$  difference between age groups:  $t_{(19)}=5.96,$ 

 $p<0.001,\ d=2.60$ ]. Finally, the effect of upright semi-tandem stance on decrements in cognitive-cognitive dual tasks compared to cognitive single tasks were more pronounced in old (difference in cognitive dual-task effect in standing vs. sitting; M=0.14; SE=0.03) compared to young adults  $[M=0.03;\ SE=0.02,\ difference between age groups: <math>t_{(19)}=3.01,\ p=0.007,\ d=1.32$ ]. As the direction of the effects of upright stance on the interaction effects between modality compatibility and cognitive single task vs. dual task was the same for both groups of participants, no 4-way interaction was detected.

In sum, the cognitive performance data showed that aging affects the processing of cognitive-postural dual tasks in several ways. Besides a general performance decrement compared to young adults, cognitive-cognitive dual-task performance in old adults was severely impaired. This effect was particularly

TABLE 5 | Statistical analyses of cognitive performance data (n = 10 young participants, n = 11 old participants).

Factor/Interaction	F-value	p-value	Partial Eta square
MAIN EFFECTS			
Group	$F_{(1, 19)} = 21.76$	< 0.001	0.53
Modality compatibility	$F_{(1, 19)} = 70.86$	< 0.001	0.79
Cognitive Single vs. Cognitive Dual	$F_{(1, 19)} = 49.77$	< 0.001	0.72
Sit vs. Stand	$F_{(1, 19)} = 21.48$	< 0.001	0.53
INTERACTIONS OF TASK FACTORS			
Modality Compatibility × Cognitive Single vs. Cognitive Dual	$F_{(1, 19)} = 92.21$	< 0.001	0.83
Modality Compatibility $\times$ Sit vs. Stand	$F_{(1, 19)} = 8.50$	0.009	0.31
Cognitive Single vs. Cognitive Dual Task $\times$ Sit vs. Stand	$F_{(1, 19)} = 23.71$	< 0.001	0.56
Modality Compatibility $\times$ Cognitive Single vs. Cognitive Dual $\times$ Sit vs. Stand	$F_{(1, 19)} = 1.96$	0.177	0.09
INTERACTIONS WITH GROUP FACTOR			
Modality Compatibility $\times$ Group	$F_{(1, 19)} = 24.31$	< 0.001	0.56
Cognitive Single vs. Cognitive Dual × Group	$F_{(1, 19)} = 16.08$	< 0.001	0.46
Sit vs. Stand × Group	$F_{(1, 19)} = 3.51$	0.077	0.16
Modality Compatibility $\times$ Cognitive Single vs. Cognitive Dual $\times$ Group	$F_{(1, 19)} = 35.46$	< 0.001	0.65
Modality Compatibility $\times$ Sit vs. Stand $\times$ Group	$F_{(1, 19)} = 0.02$	0.891	0.001
Cognitive Single vs. Cognitive Dual Task $\times$ Sit vs. Stand $\times$ Group	$F_{(1, 19)} = 9.08$	0.007	0.32
$\label{eq:modality} \text{Modality Compatibility} \times \text{Cognitive Single vs. Cognitive Dual} \times \text{Sit vs. Stand} \times \text{Group}$	$F_{(1, 19)} = 0.65$	0.43	0.03

pronounced in the modality incompatible condition, which is assumed to require a high degree of executive control related to the coordination of concurrent response-selection processes. This decrement was further pronounced when old participants had to perform the postural task simultaneously, with a performance drop down to 0.27.

#### **Postural Task Performance**

**Figure 3** illustrates the pattern of relative multiple task costs in the comparison of modality compatible and modality incompatible tasks for the young and old age group (see **Table 6** for the according raw data). As can be seen from **Figure 3**, effects of modality compatibility on relative multiple task costs in total CoP displacements differ substantially between the young and the old age group. While the young age group showed highest CoP displacements in the modality compatible CP blocks, the old age group showed highest total CoP displacements in the modality incompatible CCP blocks, i.e., in the cognitive-cognitive-postural triple task.

A repeated measures ANOVA factoring in relative task costs for CP and CCP total CoP displacements in modality compatible and modality incompatible conditions, revealed the following results:

#### Age-Independent Task Effects

There were no significant main effects of cognitive-postural dual task (CP) vs. cognitive-cognitive-postural triple task (CCP) and modality compatibility independent of age (all ps > 0.05), but a significant interaction of CP vs. CCP task \* modality compatibility,  $[F_{(1,24)}=6.348,\ p=0.019,\ \eta^2_{\ p}=0.209].$  This interaction reflects that modality compatibility effects were generally greater in CCP task blocks (difference between modality incompatible and modality compatible: M=1.5%;

SE=2.03) than in CP blocks [M=-6.02%; SE=3.31; comparison of compatibility effects between CP and CCP,  $t_{(25)}=2.69, p=0.013, d=0.51$ ].

#### Age-Dependent Effects

Participants in the old age group had generally higher total CoP displacements during cognitive task performance, as reflected in a significant main effect of age in the analysis of the relative multiple task costs  $[F_{(1, 24)} = 8.18, p = 0.009, \eta_p^2 = 0.254].$ Also, there was an interaction of CP vs. CCP task \* age,  $F_{(1, 24)} = 8.763$ , p = 0.007,  $\eta^2_p = 0.267$ . This effect reflects that the young age group had higher CoP displacements in CP blocks compared to CCP blocks (difference between CCP and CP: M = -6.27%; SE = 2.57), while the old age group showed a trend for the expected higher total CoP displacements in CCP blocks compared to CP blocks [M = 4.66%, SE =2.51, difference between age groups:  $t_{(24)} = 2.96$ , p = 0.007, d = 1.18]. Also, there was a significant interaction effect of modality compatibility \* age,  $F_{(1, 24)} = 5.344$ , p = 0.030,  $\eta^2_p$ = 0.182. Numerically, young participants showed greater total CoP displacements in the modality compatible task blocks compared to the modality incompatible task blocks (difference between modality incompatible and modality compatible: M =-6.54%, SE = 3.45). In contrast, the old age group showed the expected pattern of greater total CoP displacements in modality incompatible task blocks compared to modality compatible task blocks [M = 3.65%, SE = 2.04, difference between age groups:  $t_{(24)} = 2.32, p = 0.007, d = 0.92$ ].

Thus, while the old age group showed the expected pattern of highest total CoP displacements in modality incompatible CCP blocks, a reversed pattern was present in the young age group, with highest total CoP displacements in modality compatible CP blocks (see **Figure 3**). This was further supported

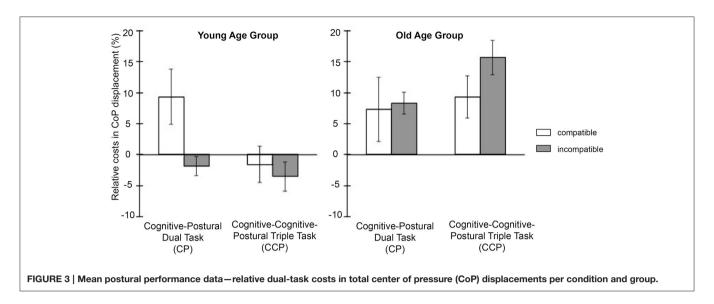


TABLE 6 | Total center of pressure (CoP) displacements P-, CP-, and CCP-task per modality compatibility condition (in mm, standard error in parentheses).

TASK				
	Postural single task (P)	Cognitive-postural dual task (CP)	Cognitive-cognitive-postural triple task (CCP	
YOUNG PARTICIPANTS	(n = 15)			
Modality compatible	464.42 (24.21)	499.57 (30.10)	449.92 (20.19)	
Modality incompatible	476.89 (25.37)	462.91 (19.21)	454.85 (19.73)	
OLD PARTICIPANTS (n =	=11)			
Modality compatible	763.87 (33.41)	809.58 (39.24)	807.12 (43.34)	
Modality incompatible	714.82 (30.83)	769.10 (32.08)	821.49 (32.50)	

by separate post-hoc independent t-tests on the differences in modality compatibility effects (i.e., difference between modality incompatible tasks and modality compatible tasks) in CP blocks and CCP blocks, respectively: in CP blocks the young age group had higher total CoP displacements for modality compatible tasks compared to modality incompatible tasks than the old age group [young: M = -11.12%; SE = 5.23; old: M = -0.1.91%; SE= 2.44; difference between age groups:  $t_{(17.9)} = 2.17$ , p = 0.044, d= 0.86], thus showing a reversed effect of modality compatibility in CP blocks in the young age group. In contrast, in CCP blocks the old age group had higher total CoP displacements than the young age group in modality incompatible tasks compared to modality compatible tasks [young: M = -1.91%; SE = 2.44; old: M = 6.29%; SE = 3.01; difference between age groups:  $t_{(24)} =$ 2.14, p = 0.043, d = 0.85]. Note, however, that the three way interaction of CP vs. CCP task \* modality compatibility \* age was not significant (p = 0.501), as absolute differences were in the same direction for both groups due to the negative values in the young age group.

### **Integration of Performance in Cognition** and Postural Control

The analysis of age-related relative dual-task costs for cognitive performance revealed generally increased relative dual-task costs for old (M = 8.95%; SE = 1.72) compared to young adults [M =3.08%; SE = 1.72;  $F_{(1, 19)} = 5.48$ , p = 0.03, partial  $\eta^2_p = 0.22$ ], i.e., higher decrements of cognitive performance when standing compared to sitting in old age. In addition, old age potentiated the relative posture-related decrements in the effect of workingmemory load  $[F_{(1, 19)} = 9.28, p = 0.007; partial <math>\eta^2_p = 0.33]$ , i.e., cognitive dual task vs. cognitive single task performance (effect size in young: M = 3.57%; SE = 1.74; old: M = 18.53%; SE = 4.4). The ANOVA including both domains (cognition vs. posture) did not reveal any interaction with the factor domain, suggesting that no (age-related) trade-offs were present in the effectiveness of the experimental manipulations.

#### DISCUSSION

This is the first study to examine age-related interference effects between input-output modality mappings and postural control. We compared the effects of age on cognitive and postural task performance to address the question, whether aging affects (i) postural control, (ii) working memory capacity in general, and/or (iii) specific executive functions related to dual-task coordination. While there is a plethora of evidence from previous cognitive-postural dual-task studies for agingrelated decrements in the domains of posture and working memory capacity, little is known about the role of specific executive functions. We hypothesized that executive functions associated with the coordination of concurrent responseselection processes related to modality compatibility (Hazeltine et al., 2006; Stelzel et al., 2006; Stephan and Koch, 2010) selectively interfered with postural control in old age. Our data provide first evidence for this assumption, showing that inputoutput modality compatibility has age-specific effects on both cognitive and postural performance over and above general age-related decline and effects related to increased working memory load. All age-related effects for the three domains will be summarized and discussed in the following.

#### **General Age-Related Decrements**

Our data replicate previous findings of cognitive performance decrements in the working-memory domain (Rajah and D'Esposito, 2005; Nyberg et al., 2012; Heinzel et al., 2014) and greater total CoP displacements during cognitive task performance (Woollacott and Shumway-Cook, 2002; Granacher et al., 2011; Boisgontier et al., 2013) in old compared to young adults. The finding of a general increase in multiple task costs for old adults support the view that independent of the specific type of cognitive task that is performed, a decline in postural stability and in cognitive information processing is present. A multitude of functional and structural changes on cortical, subcortical, and peripheral levels (Raz et al., 1997, 2005; Grady, 2012; Baudry, 2016) may account for this general performance decline in old age.

### Age-Related Effects of Working-Memory Load (Dual Task vs. Single Task)

Working-memory load, as measured by differences between cognitive-cognitive dual tasks and cognitive single tasks affected cognitive task performance more in old compared to young participants, being in line with further studies on decreases in cognitive performance in old age depending on working memory load (Sander et al., 2012). It has previously been shown that old adults are able to compensate their working-memory decline to a certain degree by recruiting additional brain regions in the lateral prefrontal cortex (Reuter-Lorenz and Cappell, 2008; Barulli and Stern, 2013; Heinzel et al., 2014, 2016). This cognitive reserve, however, is limited, and the performance drop in old adults for cognitive-cognitive dual tasks in general and in cognitive-cognitive-postural triple tasks in particular suggests that increased working memory load in multiple-task situations quickly reaches this limit.

As for postural control, effects of working-memory load showed dissociable patterns for young and old adults. While old adults showed numerically higher postural instability (i.e., larger total CoP displacements) when performing cognitive dual tasks as compared to cognitive single tasks on the force plate, the reverse was true for young adults. They showed higher postural instability in the cognitive single tasks compared to the cognitive dual tasks. While the observed effects in old age are consistent with the "limited resource hypothesis" (Kahneman, 1973; Wickens, 1980), suggesting that interference arises between cognitive and postural tasks in old age because they both require limited attentional resources (Huxhold et al., 2006), the performance pattern in the young adults does not fit into that framework. Here, we expected no substantial effects of cognitive task load on postural stability, as young adults are assumed to use attentional control and supraspinal pathways to a smaller degree to control posture (Baudry, 2016). Highest instability was obtained in the easiest task condition, i.e., when modality compatible single tasks were performed. This suggests a fundamentally different processing strategy in young adults, which will be discussed in more detail further below.

## **Age-Related Effects of Executive** Functions (Modality Compatibility)

As expected, modality compatibility affected cognitive performance in both age groups only in the dual-taskcontext. When processing two non-preferred input-output modality mappings (i.e., visual-vocal and auditory-manual) simultaneously, cognitive dual-task performance was severely impaired compared to modality compatible mappings (i.e., visual-manual and auditory-vocal). This effect was even more pronounced in the old age group and when performing the postural control task in addition (i.e., cognitive-cognitivepostural triple task). This finding extends previous studies on the effects of input-output modality compatibility in several ways. First, it shows that modality compatibility is effective in different task settings. Previous studies used simple choicereaction tasks in dual-task (Hazeltine et al., 2006; Stelzel et al., 2006; Stelzel and Schubert, 2011) and task-switching contexts (Stephan and Koch, 2010, 2011). Here, a one-back working memory task was applied, which did not require responses on every trial but only for one-back targets. Still, effects of modality compatibility were robust in both age groups and highly consistent with the findings in choice-reaction tasks. This suggests that the process of simultaneously keeping track of two modality incompatible task sets with the requirement to emit a modality incompatible response occasionally is highly similar to applying the mappings on every trial. This further supports the close coupling of stimulus and response information in a given task set (Greenwald and Shulman, 1973; Prinz, 1990; Hommel et al., 2002), including the idea that response information is activated even when the response is not executed. In addition, the present study is the first to show age-related decrements in the processing of modality incompatible dual tasks. This coincides with the assumption that the concurrent processing of two modality incompatible tasks is associated with increased demands in controlled dual-task coordination, which has been associated with the lateral frontal cortex (Szameitat et al., 2002; Schubert and Szameitat, 2003; Stelzel et al., 2006, 2008, 2009), i.e., the part of the brain, which shows most robust decrements in old age (Grady, 2012).

Concerning the effects of modality compatibility on postural control-CoP data in the old age group were all in the same direction as the effects in the cognitive performance data with selective increases in total CoP displacements in the modality incompatible dual task. Thus, for old adults the increased cognitive demands associated with the coordination of two non-preferred input-output modality mappings directly interfered with postural control. Note that the modality compatible and the modality incompatible cognitive dual tasks did not differ in terms of working-memory load, neither did the dual task involve overlap in perceptual or response requirements. Both dual tasks involved the simultaneous perception of a visual and an auditory stimulus and an equal number of manual and vocal responses. Furthermore, central code overlap (i.e., spatial codes in both tasks) was the same for modality compatible and modality incompatible dual tasks. Accordingly, the increased total CoP displacements cannot be associated with either of these factors, but must be related to other differences in central processing requirements. Consequently, we interpret the performance decrements with decrements in higher-order control processes associated with coordinating the concurrent translation of non-preferred input-output modality mappings that have been associated with activity in the lateral frontal cortex before (Stelzel et al., 2006).

That the recruitment of these frontal regions for the cognitive dual task interferes with postural control in old age is in line with age-related neuronal changes in this group. Age-related decrements in postural control has been described previously in the form of narrative reviews (Granacher, 2011; Granacher et al., 2012; Baudry, 2016) and original work (Lajoie and Gallagher, 2004; Berger and Bernard-Demanze, 2011; Granacher et al., 2011). With reference to these findings, we postulate that age-related changes in postural control are most likely caused by age-related changes in the peripheral and the central nervous system. In other words, numerous degenerative processes within the central nervous system (e.g., desensitization of mechanoreceptors, reduction number of sensory and motor neurons, reduced volume of gray and white matter in different brain areas etc.) are responsible for age-related performance decrements in postural control. Due to the complex interactions of the different structures within the postural control system and how these are affected by biological aging and physical inactivity, it is highly speculative and most likely inadequate to reduce age-related decrements in postural control to selected structures within the central nervous system.

Nevertheless, some work has been done, in an attempt to examine supraspinal mechanisms responsible for age-related changes (Jacobs and Horak, 2007; Mihara et al., 2008; Rosano et al., 2008; Baudry, 2016). For example, Rosano et al. (2008) assessed gray matter volume of five different brain regions and spatiotemporal gait parameters in older adults. Shorter steps and longer double support times were associated with smaller sensorimotor regions within the motor, visuospatial, and cognitive speed domains. These findings suggest that measures of gait in older adults living in the community are not only the consequence of underlying age-related changes in peripheral systems (i.e., neuropathology; Marchetti and Whitney, 2005), but that they also indicate underlying focal, selective changes in brain structure.

Further evidence for potential mechanisms underlying agerelated decrements in postural control comes from studies with patients examining age-related pathologies (i.e., dementia and M. Parkinson) and their impact on postural control. Mild cognitive

impairment (MCI) is often associated with changes in volume of the prefrontal cortex. Furthermore, there is evidence that MCI patients' postural control is particularly affected under dual-task conditions as opposed to age-matched healthy seniors (Montero-Odasso et al., 2012; Muir et al., 2012). In other words, it can be postulated that changes in the prefrontal cortex are associated with decrements in postural control (Sheridan and Hausdorff, 2007; Mihara et al., 2008). Moreover, Parkinson's disease is characterized by a loss of dopaminergic neurons and associated with severe decrements in postural control (e.g., freezing of gait, ataxia; Kaasinen and Rinne, 2002). Therefore, age-related changes in striato-frontal pathways appear to be directly related to postural instability.

Whether the locus of age-related changes underlying the reported decrements in the present study is the prefrontal cortex *per se* or other regions connected to the prefrontal cortex (Frank et al., 2001; Dahlin et al., 2008; Backman et al., 2011) cannot be separated in our behavioral study. Still, the present task design provides the possibility to pinpoint cognitive-postural interference effects to specific cognitive aspects relevant to dualtask processing (Meyer and Kieras, 1997; Logan and Gordon, 2001) over and above increased working-memory load. Further studies are required to more directly examine the role of executive coordinative processes in cognitive-postural dual-task situations.

Postural stability data in the young age group did not coincide with the effects of modality compatibility on cognitive performance. Increased cognitive task demands in modality incompatible dual tasks did not lead to increased total CoP displacements compared to the single motor tasks, i.e., no relative triple-task costs emerged. Instead, young participants showed greater postural sway in the seemingly easiest tasks, the modality compatible single tasks. This reversed effect in the young age group, i.e., increased postural stability and diminished multiple task cost for the most demanding task finds support by other studies reporting improved postural stability in several posturalcognitive dual-task settings (Andersson et al., 2002; Riley et al., 2003; Brauer et al., 2004; Lacour et al., 2008). This was explained by attentional effects, i.e., a change in focus regarding internal vs. external focus of attention with respect to posture depending on the task demands (Wulf and Prinz, 2001). It is assumed that as the attentional focus shifts from postural control to the cognitive task, balance will be controlled by more automatic and more efficient processes (Vuillerme and Nafati, 2007). Improvement in measures of postural control was shown in studies where the focus of attention was explicitly manipulated showing reduced body sway with an external focus of attention as compared to an internal focus of attention (McNevin and Wulf, 2002; Wulf et al., 2004). Differences in such shifts in attentional focus depending on the cognitive task requirements could provide one explanation for differential age effects. The reverse pattern of total CoP displacements in the young compared to the old age group might be further explained by an underlying inverted U-shaped non-linear interaction model (Lacour et al., 2008), i.e., for young participants task demands might have been optimal in all but the modality compatible single-task condition and therefore did not interfere with postural control. In contrast, in the old age group, already the seemingly easy modality compatible single tasks provided a challenge, which peaked in a cognitive-postural performance break down in the modality incompatible dual task. Direct manipulations of attentional focus in studies on specific executive functions in cognitive-postural dual tasks might shed further light on these mechanisms.

#### CONCLUSION

In sum, our findings provide further evidence for age-related decrements in the concurrent performance of cognitive and postural tasks. They extend previous findings by separating effects of unspecific resource limitations from specific changes in coordinating temporally overlapping task requirements. This specification of age-related decrements provides new opportunities for cognitive-postural dual-task training procedures, which should also focus on such coordinative skills. Due to the small sample size and the inclusion of female subjects only, our findings cannot be generalized to other populations and need to be interpreted with care because they are preliminary. Future studies should replicate our approach by including larger samples and males as well as females in their cohort. Also, larger samples will allow testing for the association of cognitive-postural interference with further neuropsychological measures, which would allow a more elaborate interpretation with respect to the underlying cognitive mechanisms. Still, the robustness of effects even in this small sample of rather healthy old female adults indicate the relevance

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#### **ETHICS STATEMENT**

This study was carried out in accordance with the recommendations of the ethics committee of the University of Potsdam with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the ethics committee of the University of Potsdam.

#### **AUTHOR CONTRIBUTIONS**

All authors listed have made substantial, direct and intellectual contribution to the work, and approved it for publication. CS and GS contributed equally as first authors. SH and UG contributed equally as senior authors.

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## **Cross-modal Action Complexity: Action- and Rule-related Memory Retrieval in Dual-response Control**

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Normally, we do not act within a single effector system only, but rather coordinate actions across several output modules (cross-modal action). Such cross-modal action demands can vary substantially with respect to their complexity in terms of the number of taskrelevant response combinations and to-be-retrieved stimulus-response (S-R) mapping rules. In the present study, we study the impact of these two types of cross-modal action complexity on dual-response costs (i.e., performance differences between single- and dual-action demands). In Experiment 1, we combined a manual and an oculomotor task, each involving four response alternatives. Crucially, one (unconstrained) condition involved all 16 possible combinations of response alternatives, whereas a constrained condition involved only a subset of possible response combinations. The results revealed that preparing for a larger number of response combinations yielded a significant, but moderate increase in dual-response costs. In Experiment 2, we utilized one common lateralized auditory (e.g., left) stimulus to trigger incompatible response compounds (e.g., left saccade and right key press or vice versa). While one condition only involved one set of task-relevant S-R rules, another condition involved two sets of task-relevant rules (coded by stimulus type: noise/tone), while the number of task-relevant response combinations was the same in both conditions. Here, an increase in the number of to-be-retrieved S-R rules was associated with a substantial increase in dual-response costs that were also modulated on a trial-by-trial basis when switching between rules. Taken together, the results shed further light on the dependency of cross-modal action control on both action- and rule-related memory retrieval processes.

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#### INTRODUCTION

In our daily life, we are used to do several things at the same time, that is, we routinely execute multiple actions simultaneously. In cognitive psychology, there is a long research tradition in which the underlying mechanisms of such situations are unraveled. In this context, two closely related research fields can be distinguished: Research on multitasking (specifically dual-tasking) and research on multiple-action control. Dual tasking necessarily involves the simultaneous processing of two tasks, that is, two independent streams of processing triggered by two distinct stimuli or stimulus characteristics, but irrespective of the need to finally produce (at least) two overt responses (e.g., one task may involve memorization only). In contrast, research on multiple-action control can be regarded as narrower in the sense that it only subsumes situations in which two or more

responses are overtly executed. At the same time, however, it can also be regarded as broader in the sense that it also covers situations in which one aspect of a stimulus defines the selection and execution of a dual-response compound consisting of two discriminable responses (Holender, 1980; Fagot and Pashler, 1992). Since most theories underlying the control of multiple actions were developed in the context of dual-task studies, it is important to examine whether and to which extent underlying concepts can also be transferred to those situations that involve multiple-action control but do not represent a typical dualtask situation involving two independent stimuli. In the present study, we are utilizing both approaches in two experiments (i.e., triggering two responses with (a) two separate stimuli and (b) one single stimulus) to focus on the role of action- and rule-related memory retrieval processes in multiple-action control involving distinct effector systems (i.e., oculomotor and manual responses).

Previous dual-task research has focused on explaining how two simultaneous task processing streams can interfere with each other. To define each task, instructions - in form of a set of stimulus-response rules – are explicitly presented to participants at the beginning of the experiment. Representations of these rules in working memory allow participants to correctly bind responses to stimuli in each trial, ensuring task-appropriate action (Logan and Gordon, 2001). Working memory is typically defined as a cognitive system responsible for maintenance, updating, and manipulation of task-relevant information (e.g., Baddeley and Hitch, 1974; Daneman and Carpenter, 1980; Baddeley et al., 2011). In the context of multiple-action control, working memory is thus necessary for maintaining task-relevant representations of stimuli and responses, and should also provide the basis for correctly binding stimuli and responses according to task rules. As such, it is regarded as an integral component for executive control in dual-task frameworks (e.g., Meyer and Kieras, 1997). Note that the well-known storage limitations of working memory render it impossible to maintain simultaneous representations of all potentially task-relevant stimuli, responses, and binding rules, thus calling for retrieval processes (e.g., in terms of transferring pre-activated longterm memory representations into the focus of attention in working memory, see Cowan, 1995, 2016; Mayr and Kliegl, 2000; Oberauer, 2002; Oberauer et al., 2013). In this way, response selection in multiple action control can be conceptualized as the retrieval of the correct (i.e., rule-appropriate) response (among other response alternatives) in each task based on task rules that have been correctly retrieved among potential alternative rules (see also Verbruggen et al., 2014).

Interestingly, working memory mechanisms that are specific for the coordination of multiple-action demands have only seldom been addressed explicitly (see Hazeltine and Wifall, 2011, for a detailed discussion on this issue). For example, Hommel (1998a) demonstrated that features (e.g., spatial codes) of a secondary task response, that is, a response in a Task 2 that was executed after a Task 1 response, determined the speed of the primary Task 1 response [backward crosstalk effect based on spatial response-response (R-R) compatibility]. This effect (which is based on conflict between two task-appropriate response representations) is difficult to explain when assuming

that response selection of Task 1 must be finished before any response-related processing for Task 2 occurs (i.e., within a serial response selection bottleneck account, see Pashler, 1994). To explain the backward crosstalk effect, it has been discussed whether representations of the task rules for Task 2 in working memory might already be active during Task 1 processing (due to partially automatic S-R bindings in form of memory event files, see Hommel, 1998a,b). In this way, response activation in Task 2 can prime or interfere (in the case of compatible or incompatible response codes, respectively) with response-related processing in Task 1 (see Hommel and Eglau, 2002; Ellenbogen and Meiran, 2008, 2010, for in-depth discussions). Note, however, that while the present study on a general level also addresses the interaction of multiple-action selection and memory processes, the specific focus of the present study is somewhat different: Instead of analyzing backward crosstalk effects in dual tasks, we measure dual-response coordination efficiency as indexed by dual-response costs (see below for details) and focus on retrieval competition between currently appropriate and inappropriate representations within a trial.

As outlined above - and in contrast to typical dual-task settings - multiple-action control does not necessarily involve two distinct task processing streams in form of separate response selection processes. One specific example is the case of dualresponse compounds in which two responses are triggered by the same aspect of a stimulus. Thus, interference within such dualresponse compounds cannot be readily explained by mechanisms referring to interference between independent rules (and separate response selection processes) for Task 1 and Task 2. As a response to this issue, Huestegge and Koch (2010; see also Huestegge, 2011, for an extended version) suggested an alternative framework of multiple-action control that does not involve two distinct response selection processes (one for each independent task) within a trial, but instead suggests one common "mapping selection" stage in which feature codes (e.g., spatial codes) are bound to task-relevant effector codes in accordance with task instructions. If, for example, a left auditory stimulus indicates the execution of a response compound consisting of a leftward saccade and a right manual key press, it is assumed that the mapping selection stage involves the implementation of a corresponding binding pattern among codes, that is, the binding of a "left" spatial code with the "saccade" effector code and of a "right" spatial code with a "manual" effector code. Thus, such a binding pattern specifies the required response compound (or response combination). The model also involves further assumptions. For example, more complex binding patterns (those involving more and/or potentially conflicting codes) are assumed to take more time (e.g., when two spatial codes instead of one need to be bound to respective effector systems). Finally, the model assumes that *memory-based conflict* between task-relevant binding patterns can occur in terms of retrieval competition. Specifically, persisting activation of a binding pattern from the previous trial is assumed to interfere with selecting a different binding pattern in the current trial (retrospective interference, equivalent to response repetition/switch effects in single task control, see Bertelson, 1965; see also Janczyk, 2016, for betweentrial modulations of the backward crosstalk effect in dual tasks).

Additionally, and more relevant for the present study, we assumed that all task-relevant binding patterns are activated to some extent (i.e., prepared) and thus held in memory based on task instructions (e.g., see Pfeuffer et al., 2017, on explicit rule implementation). As a result, this baseline activation of all potentially upcoming binding patterns should impact on each individual mapping selection in a current trial and make it more difficult to coordinate both responses simultaneously. A clear prediction of this assumption is that any increase in the number of task-relevant binding patterns should negatively affect dualresponse coordination efficiency, which in the present study is defined as an inverse measure of dual-response costs, that is, the additional time to execute the same response in a response compound (i.e., in dual-response condition) than in isolation (i.e., in single-response condition). This prediction of the model by Huestegge and Koch (2010) and Huestegge (2011) has not been directly addressed yet in previous research on multipleaction control, and will be tested in Experiment 1 of the present study.

A related open issue (although not directly associated with predictions from our model) is the impact of the to-be-memorized stimulus-response binding rules on dual-response coordination efficiency in multiple-action control. While the number of task rules was shown to affect backward crosstalk effects in dual tasks (see Hommel and Eglau, 2002; Ellenbogen and Meiran, 2008, 2010), the question of how the number of instructed task rules affects dual-response coordination efficiency in response compound control (where a single stimulus defines both responses) is still an open issue. Experiment 2 of the present study will address this issue in order to further specify the potential interactions between memory (here: related to the number of task rules) and multiple-action control.

Across both experiments, we thus study the impact of response binding pattern retrieval (by manipulating the number of task-relevant response binding patterns while keeping the amount of S-R rule sets constant; Experiment 1) and rule retrieval (by manipulating the number of task-relevant rule sets while keeping the number of task-relevant response binding patterns constant; Experiment 2). Both manipulations have in common that they are associated with an increase/decrease of the complexity of memory demands (i.e., the amount of retrieval competition) in multiple-action control. Specifically, we focus on effects of these factors on dual-response coordination efficiency (see above). Note that this current focus on dualresponse costs as a dependent measure differs substantially from just analyzing effects on overall RTs in each effector system, because absolute RT levels reflect more basic phenomena that are not necessarily specific for multiple-action control. In contrast, dual-response costs are typically regarded as an index of dualresponse interference (e.g., Navon and Miller, 1987; Schumacher et al., 2001; Huestegge and Koch, 2009), and as such should reflect the ability (or efficiency) to coordinate two responses as a function of the complexity of memory demands. Following a research tradition in our lab (Huestegge and Koch, 2009, 2010; Huestegge and Adam, 2011; Pieczykolan and Huestegge, 2014), we focused on cross-modal action demands involving both oculomotor and manual actions. We considered this

combination of effector systems particularly interesting, since previous research has suggested different underlying control characteristics as a function of response selection difficulty for the two effector systems (e.g., manual responses follow Hick's law while oculomotor responses do not, see Kveraga et al., 2002).

#### **EXPERIMENT 1**

In Experiment 1, we combined a manual and an oculomotor task, each involving four response alternatives. Specifically, we decided to vary the overall number of binding patterns by manipulating the number of response alternatives in the oculomotor response (while keeping manual response alternatives constant). Therefore, any differences in dualresponse costs for the manual response can only be attributed to the specific influence of the dual-response condition and not to a difference of the number of response alternatives in single-response conditions. Both types of responses (manual and oculomotor) were triggered by separate stimulus features. Crucially, one (unconstrained) condition involved all 16 (4\*4) possible combinations of response alternatives (i.e., of binding patterns), whereas a constrained condition only involved a subset of combinations (i.e., 8) to manipulate the number of relevant cross-modal response binding patterns. Specifically, in the constrained condition we limited the range of oculomotor response alternatives from four target positions to two target positions. This was implemented to focus the analysis on the manual responses, for which all aspects of the design are comparable regarding the number of response alternatives (i.e., 4) and which exhibit the larger amount of dual-response costs (based on previous studies of this response combination, see Huestegge and Koch, 2009, 2010, 2013; Pieczykolan and Huestegge, 2014) and which therefore should be more sensitive to manipulations affecting dual-response situations. As outlined in the introduction and based on the framework by Huestegge and Koch (2010; see also Huestegge, 2011) we tested the hypothesis that manual dual-response costs are larger in the unconstrained (vs. constrained) response pattern condition, which would suggest that the number of task-relevant mapping patterns stored in memory affects dual-response coordination efficiency.

#### Method

#### **Participants**

Forty-eight participants were randomly assigned to two groups (unconstrained vs. constrained binding patterns group). The mean age was 24.6 years in the unconstrained group (SD=3.7, range = 19–33, nine male) and 23.8 years in the constrained group (SD=4.1, range = 17–34, four male). All participants gave informed consent and received monetary reimbursement or course credits for participation.

#### Apparatus and Stimuli

Participants were seated in front of a standard 21" CRT screen. Eye movements of the right eye were recorded at a sampling rate of 1000 Hz using an Eyelink 1000 eye tracker (SR Research, Ottawa, ON, Canada). On a black background, a gray central

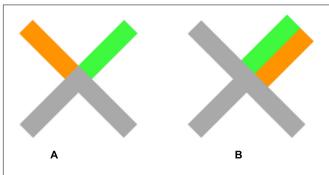


FIGURE 1 | Examples of a central stimulus in the incompatible condition (A) and compatible condition (B) in Experiment 1.

fixation cross (30 px × 30 px in X shape, see Figure 1) as well as four gray rectangular saccade targets (squares with an edge length of 20 px) located at 9.4° diagonally at the upper left, upper right, lower left, and lower right remained present throughout. As manual response keys, four keys (in a square-like spatial arrangement) from the standard keyboard were chosen (upper left, upper right, lower left, and lower right key) and marked with gray stickers. The visual stimuli were represented as color changes of one line of the limbs of the central fixation cross (Figure 1). For example, an eye movement to the upper left target combined with a manual response with the upper right key was indicated as an orange limb pointing toward the corresponding saccade target and a green limb indicating the corresponding manual key. In the case of compatible saccade and manual response demands (e.g., both "upper right"), one limb of the central "X" was half green and half orange but of the width of two limbs.

#### **Procedure**

Each trial started with the presentations of the central fixation cross (400 ms) which then changed partially in color to represent the visual imperative stimulus (with a duration of 350 ms). Participants were instructed to either move their gaze to the spatially compatible square on the screen (single saccade blocks), to press the compatible key (left/right index fingers and thumbs operating the four keys in the manual task), or to do both (dualresponse blocks) as fast and accurately as possible. While in the unconstrained group all combinations of manual and oculomotor responses were possible, thus all 16 binding patterns were present, in the constrained group the range of potential saccade alternatives was reduced to two resulting in a reduction of the number of total response binding patterns (8 in total). However, participants were not explicitly informed about this constraint, and all four saccades targets were still visible in the constrained group in order to obtain a comparable visual stimulus display. In conditions that required saccades (saccade response in single and dual-response blocks), subjects were instructed to return to the central fixation cross after responding. Each participant completed nine blocks in total consisting of three sequences of the experimental blocks (single manual, single saccade, dual). The order within the sequences was counterbalanced across participants but was constant within participants (e.g., one participant completed the sequence "manual, dual, saccade" three

times). Within each block, 48 stimuli were presented in random order with an inter-stimulus interval of 2500, 3000, or 3500 ms that was counterbalanced across all instances of binding patterns. Prior to each block, subjects underwent a calibration routine.

#### Design

Each effector (manual, saccade) was analyzed separately with the main focus on effects on the (comparable) manual responses. Response condition (single vs. dual response) was manipulated within-participants while the number of response patterns (constrained vs. unconstrained) was varied between-participants. The order of single-response blocks and dual-response blocks as well as the color-effector assignment were counterbalanced across participants. Dependent variables were RTs and error rates (response omissions/wrong response targets).

#### **Results and Discussion**

One participant in the unconstrained group was excluded from the analyses because of extraordinary high error rates in several conditions (>60%). Thus, the final analysis refers to 23 participants in the unconstrained group and 24 participants in the constrained group. Because the number of response alternatives varied only for saccade responses, we calculated two separate ANOVAs for saccades and manual responses. RT analyses were performed on correct trials only, while trials with erroneously executed saccades in single manual condition were considered invalid and therefore excluded from the analysis (2.1% of the collected data). Additionally, we excluded compatible trials (i.e., those trials in which both responses were directed toward the same direction) from the analysis (25% of the dual-response trials; see Appendix for an analysis of R–R compatibility effects).

#### Manual Responses

A mixed 2 (response condition) × 2 (group) ANOVA revealed a significant main effect of response condition on manual RTs, F(1,45) = 473.08, p < 0.001,  $\eta_p^2 = 0.913$ , indicating longer RTs in dual- vs. single-response conditions (1050 ms vs. 488 ms). This finding replicates many previous reports of manual response sensitivity to additional oculomotor response demands (e.g., Huestegge and Koch, 2009, 2010, 2013; Huestegge, 2011; Pieczykolan and Huestegge, 2014). There was no significant main effect of the number of binding patterns, F(1,45) = 2.57, p = 0.116. Importantly, however, there was a significant interaction of response condition and the number of binding patterns, F(1,45) = 7.15, p = 0.010,  $\eta_p^2 = 0.137$ , indicating larger dual-response costs for manual responses in the unconstrained vs. constrained group (619 ms vs. 496 ms, see Figure 2). Thus, the main hypothesis of Experiment 1 was confirmed by the data: A larger number of task-relevant binding patterns increases dual-response interference and thus decreases dualresponse coordination efficiency, most likely due to greater retrieval competition between binding patterns. This result clearly demonstrates that dual-response coordination efficiency is not simply determined by the number of response alternatives for the individual tasks (which was held constant). Probably, even though responses were triggered by separate stimuli, in dual-response conditions the representation of the number of

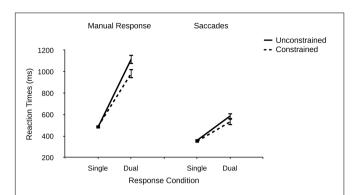


FIGURE 2 | Reaction times (ms) for manual responses and saccades as a function of response condition (single vs. dual) and number of binding patterns (unconstrained vs. constrained) in R-R incompatible trials in Experiment 1. Error bars denote standard errors.

response alternatives for the saccade response "spilled over" into that for the manual responses (which are known to be susceptible to manipulations of response alternatives), and this crosstalk-like effect may have elevated RTs in the unconstrained condition compared with the constrained condition.

Based on the same data as in the manual RT analysis, we also analyzed *error rates* to rule out a speed-accuracy tradeoff (in terms of reversed result patterns in the error data) as a potential alternative explanation. However, the data pattern did not support the notion of speed-accuracy tradeoffs (**Table 1**). While we observed a significant main effect of response condition, F(1,45) = 32.87, p < 0.001,  $\eta_p^2 = 0.422$ , indicating a greater manual error rate in dual- vs. single-response conditions (9.6% vs. 2.6%), we observed neither a significant main effect of the number of response patterns, F < 1, nor a significant interaction, F < 1.

#### Saccades

An analysis analog to that for manual responses was conducted for saccade responses. There was a significant main effect of response condition, F(1,45) = 144.29, p < 0.001,  $\eta_p^2 = 0.762$ , indicating longer saccade RTs in dual- vs. single-response conditions (561 ms vs. 357 ms), replicating previous reports of saccade response sensitivity to additional manual response demands (e.g., Huestegge and Koch, 2009, 2010, 2013; Huestegge, 2011; Pieczykolan and Huestegge, 2014). There was no significant

TABLE 1 | Error rates (%) for manual responses and saccades in R-R incompatible trials as a function of number of binding patterns (constrained vs. unconstrained), and response condition (single and dual) in Experiment 1.

Number of binding patterns	Constrained		Unconstrained	
Response condition	Single	Dual	Single	Dual
Manual responses	2.9 (0.7)	10.3 (1.5)	2.3 (0.7)	8.8 (1.6)
Saccades	2.1 (0.4)	11.8 (1.4)	1.7 (0.5)	13.5 (1.5)

Numbers in parentheses denote standard errors.

effect of the number of binding patterns, F(1,45) = 1.24, p = 0.271, and no significant interaction, F(1,45) = 1.85, p = 0.180.

The analysis of *saccade errors* revealed a significant main effect of response condition, F(1,45) = 107.17, p < 0.001,  $\eta_p^2 = 0.704$ , indicating a greater saccade error rate in dual- vs. single-response conditions (12.7% vs. 1.9%). However, there was neither a significant main effect of the number of binding patterns, nor a significant interaction, both Fs < 1.

#### **EXPERIMENT 2**

In Experiment 2, we aimed at studying the effects of the number of task-relevant rule sets stored in memory on dual-response coordination efficiency, while keeping the number of taskrelevant response combinations (i.e., binding patterns) constant. We used one common lateralized auditory stimulus (presented either to the left or right ear) to trigger incompatible response compounds (e.g., a left saccade and a right key press, or vice versa). Instead of four response alternatives (as in Experiment 1), there were only two response alternatives for each effector system (left/right saccade and left/right key press). Response demands across effector systems were always spatially incompatible (see also Huestegge and Koch, 2010; Pieczykolan and Huestegge, 2014), resulting in only two possible response compounds (i.e., two binding patterns) in this experiment (saccade left + manual key press right and saccade right + manual key press left). Using only incompatible response demands allowed us to manipulate the number of task rule sets (both task rule sets being of similar difficulty) without changing the number of taskrelevant response compounds: Crucially, while one condition only involved one set of task-relevant rules, another condition involved two sets of task-relevant S-R rules (coded via auditory stimulus type: noise vs. tone). For example, in the one S-R rule condition a tone signaled an S-R compatible saccade and an S-R incompatible key press. Consequently, a tone on the left required a leftward (compatible) saccade and a right (incompatible) key press while a tone on the right required a compatible (right) saccade and an incompatible (left) key press (one rule set: saccade compatible, manual incompatible). In the two S-R rule condition, both stimulus types were presented in an intermixed manner (two rule sets: tone saccade compatible, manual incompatible, noise saccade incompatible, manual compatible). Crucially, this resulted in the situation that the same response binding pattern (e.g., saccade left + manual key press right) could be triggered by two different stimuli (e.g., a tone on the left or a noise burst on the right). Note that unlike in Experiment 1, the number of response binding patterns (2) remained constant throughout the experiment. Therefore, if only the number of relevant response binding patterns determined the efficiency of dual-response control, we should expect similar dual-response costs in the one-rule vs. two-rule condition. However, if the number of S-R rule sets (and the associated rule retrieval from memory) affected dual-response control efficiency, we should observe substantially greater dual-response costs in the two-rule (vs. one-rule) condition.

#### Method

#### **Participants**

Twenty-four new participants (mean age  $= 23.61 \ SD = 4.42$ , range = 19-41, 20 female) with normal or corrected-to-normal vision were tested. They gave informed consent and received course credits or monetary reimbursement for participation.

#### Apparatus and Stimuli

An Eyelink II was utilized as eye-tracking device. The central fixation cross consisted of a green plus sign, and two saccade targets (at 8° to the left and right of the fixation cross) were presented in form of two green squares (1/3° each), which remained present throughout. Different to Experiment 1, we used auditory stimuli consisting of lateralized harmonic tones (with a fundamental frequency of 400 Hz mixed with 800 and 1200 Hz) and pink noise bursts (both with a duration of 50 ms) that had equal loudness and were presented via headphones.

#### **Procedure**

In each trial, an auditory stimulus was presented to the left or right ear. Participants were instructed to respond as fast and accurately as possible either by moving their gaze to a square on the screen (saccade response in single blocks), pressing a key (left/right index fingers operating two keys with a distance of 30 cm from the bottom row of a standard keyboard), or both (dual-response blocks). In the dual-response blocks, both responses were instructed to be executed spatially incompatible to each other. That is, there were only two response compounds in this experiment (saccade left + manual key press right and saccade right + manual key press left). Crucially, while the one-rule condition only involved one set of single task-relevant S-R rules (e.g., tone compatible saccade + incompatible manual response), the two-rule condition involved two opposing sets of task-relevant S-R rules (each set of rules coded via a respective auditory stimulus type: noise vs. tone; e.g., tone compatible saccade + incompatible manual response, noise incompatible saccade + compatible manual response). Thus, in one condition there was only one stimulus type (only tone or only noise), while the other condition involved both stimulus types (tone and noise).

The specific S–R assignments of stimulus types to response compounds was constant within participants and counterbalanced across participants. Each participant completed 12 blocks consisting of 36 trials each. Within each block, stimuli to the left and right were presented in randomized sequence with a response-stimulus interval of 1500, 2000, or 2500 ms. Prior to each block, subjects underwent a calibration routine.

#### Design

Due to comparable demands in both effector systems, effector modality was included here as a factor in the analysis. Thus, the within-subject variables were modality (saccade vs. manual response), response condition (single vs. dual), and the number of S–R rule sets (one vs. two). The order of single-response blocks and the two types of dual-response blocks (one S–R rule set vs. two S–R rule sets) were counterbalanced across participants. Dependent variables were RTs and error rates.

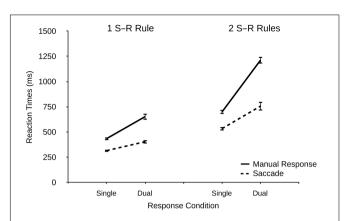


FIGURE 3 | Reaction times (ms) for manual responses and saccades as a function of response condition (single and dual) and number of S-R rule sets (1 vs. 2) in Experiment 2. Error bars denote standard errors.

#### **Results and Discussion**

Two participants were excluded due to extraordinary high error rates (>60%). Response times are depicted in **Figure 3** and error rates are shown in **Table 2**. RT analyses included only correct trials. Trials with erroneously executed saccades in single manual condition were considered invalid and therefore excluded from the analysis (1.6% of the collected data).

#### **Response Times**

There was a significant effect of response modality on RTs, F(1,21) = 206.873, p < 0.001,  $\eta_p^2 = 0.908$ , indicating faster RTs for saccades vs. manual responses (503 ms vs. 703 ms). There was also a significant main effect of response condition, F(1,21) = 226.44, p < 0.001,  $\eta_p^2 = 0.915$  (single: 497 ms, dual: 757 ms), and a significant main effect of the number of S-R

TABLE 2 | Error rates (%) for manual responses and saccades as a function of task condition (single vs. dual) and number of S–R rule sets in Experiment 2.

	1 S-R Rule		2 S-R Rules	
	Single response	Dual response	Single response	Dual response
Manual responses	1.7 (0.4)	3.4 (0.9)	9.7 (2.5)	17.1 (3.4)
Saccades	7.7 (2.4)	11.7 (2.7)	15.9 (3.5)	23.7 (3.9)

Numbers in parentheses denote standard errors

TABLE 3 | Error rates (%) for manual responses and saccades in the two-rule sets condition as a function of task condition (single vs. dual) and rule transition (repetition vs. switch) in Experiment 2.

	Single response condition		Dual response condition	
	Repetition	Switch	Repetition	Switch
Manual responses	8.1 (2.0)	11.2 (2.6)	13.6 (3.6)	22.1 (3.3)
Saccades	13.4 (3.5)	18.6 (3.5)	24.6 (4.3)	25.4 (4.0)

Numbers in parentheses denote standard errors.

rule sets, F(1,21) = 265.93, p < 0.001,  $\eta_p^2 = 0.927$  (one S–R rule: 452 ms, two S–R rules: 801 ms). Thus, manipulating the number of S–R rule sets had a very pronounced effect on overall performance.

There was a significant interaction of modality and response condition, F(1,21) = 95.60, p < 0.001,  $\eta_p^2 = 0.820$ , indicating larger dual-response costs for manual responses than for saccades (365 ms vs. 156 ms). There was also a significant interaction of modality and the number of S-R rule sets, F(1,21) = 52.54, p < 0.001,  $\eta_p^2 = 0.714$ , suggesting a stronger effect of the number of S-R rule sets in manual responses than in saccades (413 ms vs. 284 ms). Most importantly, and in line with our prediction, there was a significant interaction of response condition and the number of S-R rule sets, F(1,21) = 33.83, p < 0.001,  $\eta_p^2 = 0.617$ , indicating greater dual-response costs when two (vs. one) S-R rule sets were present (368 ms vs. 153 ms), thus demonstrating that despite the same number of response alternatives the number of rule sets strongly contributed to dual-response efficiency. Finally, the three-way interaction was significant, F(1,21) = 37.18, p < 0.001,  $\eta_p^2 = 0.639$ , indicating that the effect of greater dual-response costs under two (vs. one) S-R rules was more pronounced for manual responses (513 ms vs. 218 ms) than for saccades (223 ms vs. 87 ms).

#### **Error Rates**

Error rates are shown in **Table 3**. There was a significant effect of response modality on error rates, F(1,21)=18.58, p<0.001,  $\eta_p^2=0.469$ , indicating the usual finding of higher error rates for saccades vs. manual responses (14.8% vs. 8.0%, see, e.g., Huestegge and Koch, 2009, 2010, 2013). There was also a significant main effect of response condition, F(1,21)=6.99, p=0.015,  $\eta_p^2=0.250$  (single: 8.8%, dual: 13.9%), and a significant main effect of the number of S–R rule sets, F(1,21)=33.84, p<0.001,  $\eta_p^2=0.617$  (one S–R rule: 6.1%, two S–R rules: 16.6%). There were no significant (two-way/three-way) interactions with respect to error rates (all Fs<1 except for the response condition\* number of S–R rule sets interaction: F(1,21)=1.99, p=0.174). Taken together, the error analysis shows that the interpretation of the effects of the number of S–R rule sets on RTs is in no way compromised by any speed-accuracy trade-offs.

#### **Rule Transition Effects**

Additionally, we analyzed the data of the two-rule condition in more detail as a function of local rule transitions (rule repetitions vs. rule switches), response modality (manual response vs. saccade), and response condition (single vs. dual). If our assumption of additional rule retrieval processes in conditions involving two rules is correct, we should observe corresponding performance costs for rule switches. RTs are shown in **Figure 4**.

We found a significant main effect of rule transition, F(1,21)=77.62, p<0.001,  $\eta_p^2=0.779$ , with M=919 ms for switches vs. M=718 ms for repetitions. This result demonstrates that task rule switches affected performance, most likely reflecting interference due to retrieving or activating the task-relevant rule (or inhibiting the task-irrelevant rule). Furthermore, there were significant main effects of modality, F(1,21)=177.74, p<0.001,  $\eta_p^2=0.890$  (manual responses: 975 ms, saccades: 662 ms) and

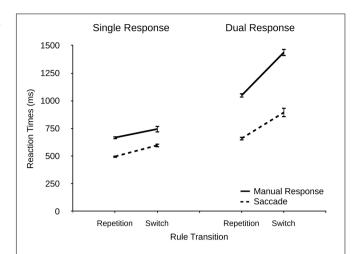


FIGURE 4 | Reaction times (ms) for manual responses and saccades as a function of rule transition (repetition and switch) and response condition (single and dual) in the two-rule condition in Experiment 2. Error bars denote standard errors.

response condition, F(1,21) = 121.21, p < 0.001,  $\eta_p^2 = 0.846$  (single: 627 ms, dual: 1011 ms).

There was a significant interaction of modality and response condition, F(1,21) = 64.48, p < 0.001,  $\eta_p^2 = 0.746$ , indicating larger dual-response costs for manual responses (537 ms) than for saccades (231 ms), and a significant interaction of modality and rule transition, F(1,21) = 6.78, p = 0.016,  $\eta_p^2 = 0.236$ , showing larger rule switching costs for manual responses (234 ms) than for saccades (167 ms). Interestingly, the interaction of response condition and rule transition was also significant, F(1,21) = 28.50, p < 0.001,  $\eta_p^2 = 0.564$ , indicating that rule switching costs were larger in dual-response conditions (312 ms) that in single-response conditions (89 ms). This finding reveals that rule retrieval interfered with dual-response coordination efficiency in that rule retrieval elevated dual-response costs in switch trials compared to repetition trials. This result was further qualified by a three-way interaction, F(1,21) = 14.27, p = 0.001,  $\eta_p^2 = 0.393$ , showing that rule switching costs were similar in single-response conditions for both response modalities (manual responses: 77 ms, saccades: 101 ms) while they differed pronouncedly in dual-response conditions (manual responses: 389 ms, saccades: 235 ms), thus resembling the results from the main analysis which indicated larger interference effects for manual responses.

There was a significant effect of response modality on error rates, F(1,21)=12.13, p=0.002,  $\eta_p^2=0.355$ , indicating the typical finding of higher error rates for saccades than for manual responses (20.5% vs. 13.8%). There was also a significant main effect of response condition, F(1,21)=6.69, p=0.017,  $\eta_p^2=0.233$  (single: 12.8%, dual: 21.4%), and a significant main effect of rule transition, F(1,21)=14.42, p=0.001,  $\eta_p^2=0.396$ , with overall switching costs of 4.4% points (19.3% vs. 14.9%). There were no significant two-way interactions (all Fs<1 except for the modality\*transition interaction: F(1,21)=2.587, p=0.122). However, the three-way interaction was significant,

F(1,21)=8.05, p=0.010,  $\eta_p^2=0.268$ , suggesting that switching costs differed more pronouncedly between response modalities in dual-task conditions (switching costs of 8.5% for manual responses and 0.8% for saccades) than in single-task conditions (manual responses: 3.1%, saccades: 5.2%). Taken together, the error analysis shows that the interpretation of the switching effects on RTs is in not compromised by any speed-accuracy trade-offs.

#### **GENERAL DISCUSSION**

The present study addressed two important research questions in the domain of multiple-action control in order to address the interplay of action control and mechanisms of maintenance and retrieval in working memory: In Experiment 1, we studied the impact of the number of task-relevant binding patterns while keeping the number of instructed S-R rule sets constant, whereas in Experiment 2 we studied the impact of the number of task-relevant S-R rule sets while keeping the number of taskrelevant binding patterns constant. Based on previous theory, we hypothesized that both manipulations should lead to retrieval competition (either between relevant response bindings or S-R rule sets), which should not only elevate overall performance (in terms of increased RTs and/or error rates) but more specifically affect dual-response coordination efficiency, which is reflected in the amount of dual-response costs (i.e., the difference between dual- and single-response performance). The present research questions were addressed in a setting involving the combination of oculomotor and manual responses.

As a main result, we found that indeed dual-response coordination efficiency (as indicated by dual-response costs in RTs) was affected by retrieval competition regarding both the number of task-relevant binding patterns (Experiment 1) and the number of task-relevant S-R rule sets (Experiment 2). A numerical comparison of effect sizes suggests that the higherlevel (rule-based) manipulation in Experiment 2 had a much stronger effect than the more basic (response combination-based) effect in Experiment 1, suggesting that it is easier for participants to cope with an increase of response complexity within one common rule than with an increase in the number of task rules (despite the same amount of possible responses in the onerule vs. two-rule condition). Specifically, the analysis of local rule switch effects in Experiment 2 suggested that dual-response performance (and not only response times in general) suffered substantially after rule switches (compared to rule repetitions), indicating that rule retrieval specifically affected dual-response coordination.

The present results extend previous theoretical claims in the dual-task control literature. For example, Ellenbogen and Meiran (2008) claimed that dual-task costs might be attributed to conflicts that arise when during the execution of one task rules for another task need to be held active in memory in order to enhance preparation for the latter. This can, for example, yield parallel activation of response codes, which can thus interfere and produce crosstalk phenomena (see also Hommel, 1998a; Hommel and Eglau, 2002). Our present Experiment 1, which

represents a typical dual-task experiment (i.e., in form of a manual and a saccade task triggered by separate stimuli), shows that even when the instructed task rules are held constant (i.e., for both effector systems participants were instructed to initiate a response which is spatially compatible with the stimulus), the actual size of the set of task-relevant response binding patterns plays an additional important role in determining the efficiency of task coordination, even across highly different response modalities such as manual and oculomotor responses. Experiment 2 also extends the claims of rule-based conflict as a major determinant of dual-response control efficiency by showing that S-R rule-based conflict not only affects dualresponse performance in typical dual-task settings (i.e., with two separate stimuli as in Experiment 1), but also when response compounds are triggered by a single dimension of a stimulus. Note that manipulating the number of S-R rule sets by utilizing opposing S-R mappings for the two rules in Experiment 2 was also associated with dimensional overlap between S-R rule sets (i.e., responses were bivalent). Therefore, the observed effects might not only have occurred due to the different number of S-R rule sets alone, but might additionally be based on response-based conflict across trials (e.g., Meiran, 2000; Brass et al., 2003). Therefore, future research could explore effects of the number of S-R rule sets in the absence of potential interference between S-R rule sets. Taken together, the present results represent a step forward in understanding the interaction of memory and action selection in the context of multiple-action control.

Our observations, especially those in Experiment 1, further strengthen our proposed framework of multiple-action control (Huestegge and Koch, 2010, see introduction) by confirming a prediction that was not explicitly tested previously, namely that the number of task-relevant binding patterns affects the efficiency of the coordination of two responses during action selection (as indexed by the amount of dual-response costs). This result further emphasizes that any model of dual-task control that only focuses on mechanisms within a trial (e.g., Pashler, 1994; Meyer and Kieras, 1997; Navon and Miller, 2002; Tombu and Jolicoeur, 2003) is necessarily incomplete, since contextual factors (e.g., which binding patterns are required in surrounding trials) strongly determine action selection efficiency (see also Janczyk, 2016). Our observation of rule switch costs further strengthens this claim by demonstrating that maintaining two rules in working memory affected dual-response efficiency on a trial-by-trial basis. The present results further highlight that it is important to study the interaction of action control and memory in order to specify the largely elusive notion of "response selection" in dual-task control models.

An interesting additional observation in Experiment 1 was that the number of response alternatives did not strongly affect overall RTs (Hick's law) in oculomotor control. While it should be noted that the underlying group comparison might be less powerful than a within-subjects design, the absence of Hick's law for oculomotor responses is well in line with previous studies (e.g., Kveraga et al., 2002). Interestingly, although for manual responses the number of response alternatives did not differ between groups (thus no effect in single-response

conditions was expected) we found a strong modulation of manual (but not oculomotor) dual-response costs when the number of alternatives in the oculomotor response varied, thus indicating a decrease of response coordination efficiency with a larger number of binding patterns. This result pattern suggests that it is important to analyze measures of coordination costs and not only overall RT levels when studying the impact of response alternatives in the context of multiple-action control. Additionally, the potential dependency of underlying mechanisms on the specific effector systems involved calls for further research utilizing other combinations of output systems (e.g., Huestegge and Hazeltine, 2011; Stephan et al., 2013; Huestegge et al., 2014).

In sum, the present study on cross-modal multiple action control demonstrated that retrieval competition between taskrelevant response binding patterns and task rules both have a strong impact on complex action control. These results further highlight the importance of studying the interplay of memory and action control (here: retrieval competition) in order to specify the mechanisms underlying the rather vague notion of response selection in multiple action control.

#### **ETHICS STATEMENT**

All procedures performed in studies involving human participants were in accordance with the ethical standards of the national research committee of the DGPs (Deutsche Gesellschaft für Psychologie) with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki (1964). The protocol was approved by the Deutsche Forschungsgemeinschaft (DFG) within the grant HU

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1847/3-1. This article does not contain any studies with animals performed by any of the authors.

#### **AUTHOR CONTRIBUTIONS**

LH had the idea for the study. AP and LH conjointly designed experiments and wrote and revised the manuscript. AP programmed the experiments and analyzed the data.

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#### SUPPLEMENTARY MATERIAL

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## **Differential Impact of Visuospatial** Working Memory on Rule-based and **Information-integration Category** Learning

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Previous studies have indicated that the category learning system is a mechanism with multiple processing systems, and that working memory has different effects on category learning. But how does visuospatial working memory affect perceptual category learning? As there is no definite answer to this question, we conducted three experiments. In Experiment 1, the dual-task paradiam with sequential presentation was adopted to investigate the influence of visuospatial working memory on rule-based and information-integration category learning. The results showed that visuospatial working memory interferes with rule-based but not information-integration category learning. In Experiment 2, the dual-task paradigm with simultaneous presentation was used, in which the categorization task was integrated into the visuospatial working memory task. The results indicated that visuospatial working memory affects information-integration category learning but not rule-based category learning. In Experiment 3, the dualtask paradigm with simultaneous presentation was employed, in which visuospatial working memory was integrated into the category learning task. The results revealed that visuospatial working memory interferes with both rule-based and information-integration category learning. Through these three experiments, we found that, regarding the rule-based category learning, working memory load is the main mechanism by which visuospatial working memory influences the discovery of the category rules. In addition, regarding the information-integration category learning, visual resources mainly operates on the category representation.

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#### INTRODUCTION

Categorization is a fundamental decision-making process that allows us to meaningfully parse the world and group similar objects together so that they can be treated equivalently (Rabi and Minda, 2014). It enables us to apply what we have learned about one thing and generalize that knowledge to other things of the same kind. For example, after learning the hard way that a

Abbreviations: COVIS, competition between verbal and implicit systems model; II, information-integration; II-C, information-integration category structure control group; II-V, information-integration category structure experimental group; RB, rule-based; RB-C, rule-based category structure control group; RB-V, rule-based category structure experimental particular mushroom is probably poisonous, it is highly adaptive to generalize that knowledge to other similar mushrooms rather than to have to learn the hard way every time a new mushroom is encountered (Richler and Palmeri, 2014).

A large number of studies have indicated that category learning contains multiple classes of processing systems (Maddox et al., 2004; Richler and Palmeri, 2014; Xing and Sun, 2015), which have been explained by different theoretical models, such as exemplar-similarity (Patalano et al., 2001), family-resemblance (Yamauchi and Markman, 1998), and so on. The COVIS is so far the most influential multi-system theory, according to which there are at least two independent systems that exist in human category learning. One is the verbal system that is based on hypothesis testing and is under the control of consciousness, which is also influenced by working memory. The other is an implicit system that solves categorization tasks by learning to associate a response with regions of perceptual space, which is based on reinforcement and is independent of working memory (Ashby et al., 1998).

This has led to an extensive series of studies that have compared the learning of RB and II category structures (Figure 1). Given that the categorization of the RB and II structures depends primarily on the verbal and implicit systems, respectively, it is possible to test two kinds of prediction made by the COVIS model (Dunn et al., 2012). For the RB category structure, the classification rules are easy to verbalize and a judgment rule does not require the integration of two dimensions. For example, consider a category set in which round objects belong to one group and square objects belong to another group. These categories could be learned by applying the easy to verbalize rule that "category 1 objects are round." However, in contrast, the II category structure defines category membership according to the conjoint values on two or more dimensions using rules that are not easy to verbalize (e.g., if the size of a circle is greater than x and the orientation of a line is greater than y, then the stimulus is a member of category A). Consequently, such structures cannot be learned by the verbal system, which must eventually yield control of the response to the implicit system (Maddox et al., 2004; Worthy et al., 2013; Richler and Palmeri, 2014).

Furthermore, according to the COVIS model, working memory involves the ability to store information transiently and to perform cognitive activities, and it has different effects on the RB and II category structures. In other words, if working memory tasks are presented concurrently, the RB category learning will be disturbed, while the II category learning will not be affected; this has been verified by a large number of studies (Maddox et al., 2004; Zeithamova and Maddox, 2006; Filoteo et al., 2010). It is worth noting that the experiments mentioned above all involved verbal working memory. However, visuospatial working memory is another important type of working memory (Baddeley and Logie, 1999). There is good evidence that verbal and visuospatial working memory rely on different neural systems (Goldman-Rakic, 1998). Compared with verbal working memory, visuospatial working memory not only includes working memory load but also involves visual resources. Additionally, processing in the implicit system depends critically

on the visual stimulus's representation in the inferotemporal cortex. This representation may be disrupted by the presence of a visuospatial task (Casale and Ashby, 2008). Thus, one hypothesis is that the presence of a visuospatial working memory task will affect II category learning. However, the existing COVIS model does not distinguish the types of working memory, and previous studies have mainly focused on the effects of verbal working memory on RB and II category learning. As such, the question naturally arises of how visuospatial working memory affects the RB and II category learning.

Using the dual-task paradigm that involves simultaneous presentation of visual stimuli, Miles and Minda (2011) found that a high level of working memory load could impair the RB category learning, which confirms that working memory plays a significant role in the RB category learning. In addition, their study found that the visual processing of the visuospatial working memory task affected the II category learning, which was not related to the level of working memory load. However, the study used the RB category structure that relies on a single dimension to perform categorization, whereas the II category structure takes two dimensions into consideration; thus, the difference in the difficulty of the category structure could affect the categorization results (Sun and Xing, 2014; Zaki and Kleinschmidt, 2014). Miles and Minda (2011) believe that visuospatial working memory mainly depends on a function that influences implicit category learning, which is not related to working memory load. Nevertheless, the study did not explain how visual processing affects category learning. Moreover, Miles et al. (2014) used a simultaneous-task paradigm in which the category learning task is integrated with a verbal working memory task, and the results showed that working memory load can affect II category learning.

It can be seen that there is still much debate about the influence of visuospatial working memory on the RB and II category structure, especially about how visuospatial working memory affects II category learning. If it does affect II structure category learning, would there be any difference in the results of the above-mentioned studies? Several studies may offer some insight to solve these problems. According to the hypothesis of Zeithamova and Maddox (2007), the process of category learning may include the following steps: (1) representation of the stimulus and (2) generation and testing of a categorization rule for the RB category learning (i.e., learning of a categorization criterion for the II category learning). Thus, we suppose that if the process of category learning really includes these steps, the working memory load from the visuospatial working memory task would be critical primarily for rule generation and testing (because the verbal system depends upon working memory load), while the visuospatial resource from the visuospatial working memory task may influence the representation of the stimulus for the II category learning (because the implicit system learns the association between a region of perceptual space and an overt response).

In practical terms, the implicit category learning system establishes a connection between a specific perceptual space and the specific action, and the representation of the category stimuli is involved in the category learning. This is indicated in the study by Dunn et al. (2012) in which a Gabor mask

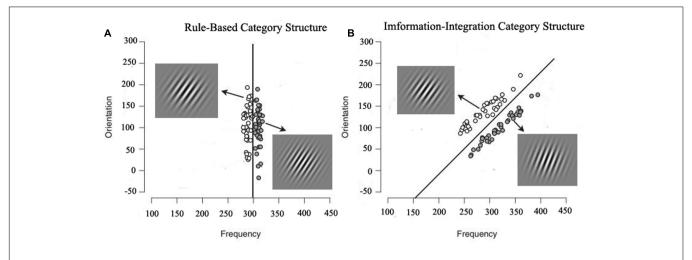


FIGURE 1 | The RB category structure and II category structure. Open circles denote Category (A) and filled circles denote Category (B). The lines represent the optimal decision boundary. In a RB category structure, decisions are made based on only one dimension (in this example, frequency), whereas in an II category structure, decisions are made based on two or more dimensions (in this example, frequency and orientation).

presented after the II category structure interfered with the visual processing of the category stimuli and affected the perceptual representation of the II category learning. Maddox et al. (2004) found that the addition of a working memory load in the sequential presentation impaired RB learning but had little effect on II learning. Furthermore, when studying the effects of working memory on category learning, dual-task paradigms are usually adopted, such as the dual task with sequential presentation and the dual task with simultaneous presentation, in which the different locations of working memory are manipulated (Miles and Minda, 2011).

Therefore, the inconsistencies in the previous studies are much more likely to be caused by the fact that visual resources and working memory load may affect the different processing stages of category learning. Based on this point of view, we conducted three experiments in which we manipulated the different dual tasks in order to examine whether they would influence the different cognitive processing stages of category learning. We aimed to investigate the process of cognitive processing during which visuospatial working memory affects II and RB category learning, especially visual resources and working memory. In Experiment 1, sequential presentation tasks were adopted. In Experiment 2, we used the embedded paradigm in which the category learning task was embedded in the visuospatial working memory task. In Experiment 3, we used a concurrent-task methodology in which the working memory task was embedded in the classification task.

# **EXPERIMENT 1**

# **Materials and Methods**

## **Participants**

We randomly selected 84 participants (40 male, 44 female) who were participating in the secondary post-graduate examination held by the education school of Guangzhou University. The

average age was 19.31 years ( $\pm 2.15$ ). All participants were right-handed, had normal or corrected-to-normal vision, and had no color blindness or color weakness problems. This study was carried out in accordance with the recommendations of the ethical committee of Guangzhou University with written informed consent from all participants. All participants gave written informed consent in accordance with the Declaration of Helsinki.

# **Experimental Materials**

The categorization stimuli were generated using the same procedures as Dunn et al. (2012). The stimuli were sine wave gratings that varied in spatial frequency and orientation. Twenty stimuli in each of the four categories were generated by sampling randomly from the same four parameter distributions used by Dunn et al. (2012). The Psychophysics Toolbox in MATLAB (MathWorks, Natick, MA, USA) was used to generate the RB and II category structures (Brainard, 1997). Actual values of spatial frequency (f) and orientation (o) were generated from a random sample (x, y) from these distributions using the following transformations: f = 0.25 + x/50,  $o = y.\pi/500$ . All of the stimuli were  $200 \times 200$  pixel images. The specific dimensions of the parameters are shown in **Table 1**.

A visuospatial working memory task was created that was analogous to the Sternberg working memory task used in Maddox et al. (2004). In this task, the participant was asked to remember four locations out of nine possible locations (analogous to remembering four numerical digits sampled from nine possible digits). First, a fixation cross (i.e., a "+") appeared in the middle of the screen, indicating the beginning of the dot pattern task. Next, nine gray dots appeared on the screen and the memory set turned red, followed by a series of four rapidly presented masks. Each mask was a 9  $\times$  9 grid of gray dots, half of which had a red center. Next, the memory probe appeared on the screen along with the question "Was this dot originally red?" Participants made a response using the appropriate button and received feedback.

TABLE 1 | Rule-based and II category structure parameters.

Category structure	μχ	μγ	$\sigma^2 \chi$	$\sigma^2\gamma$	Cov
RB					
Category A	268	93	75	75	0
Category B	268	157	75	75	0
Category C	332	93	75	75	0
Category D	332	157	75	75	0
II					
Category A	268	125	75	75	0
Category B	300	157	75	75	0
Category C	300	93	75	75	0
Category D	332	152	75	75	0

 $\mu_X$  represents the average value,  $\sigma^2_X$  represents the variance, cov represents the variance covariance, RB represents the rule-based category structure, and II represents the information-integration category structure. According to the frequency and direction, each category structure was divided into four categories: A. B. C. and D.

# **Experimental Design**

The experiment had a 2 (task condition: working memory group vs. control group)  $\times$  2 (category structure: II vs. RB)  $\times$  4 (block) repeated-measures design, in which task condition and category structure were the between-subjects variables and learning block was the within-subjects variable. The dependent variables were the accuracy of categorization in the visuospatial working memory task and the category learning. The number of participants followed that used by previous studies (Stanton and Nosofsky, 2007; Miles and Minda, 2011). All participants were assigned randomly to one of four groups, with 21 participants in each group. Two participants in the RB task control group (RB-C) were removed due to interruption during the experiment; thus, the data from 19 participants were used. One participant in the RB task experimental group (RB-V) was removed for the same reason; therefore, the data of 20 participants were used. The data of 21 participants were used in the II task experimental group (II-V), while that of 19 participants were used in the II control group (II-C) after deleting the data of two participants for the same reason.

# **Experimental Procedure**

The dual-task experimental paradigm with sequential presentation was used (**Figure 2**). The experimental procedure included four blocks, each of which had 80 trials. First, participants tried to complete the category learning task. Within each block, all 80 stimuli were presented in a random order. Participants were told to learn which of four categories (labeled as 1, 2, 3, and 4) each stimulus belonged to. After the presentation of a fixation cross (i.e., a "+") for 800 ms, the screen was presented of the RB or II category structure, which could be considered by participants as belonging to one of the four categories of A, B, C, or D, and for which they pressed the 1, 2, 3, or 4 number key on the keyboard, respectively. After the responses were given, the stimuli disappeared, and the feedback was provided immediately; the participants were informed not only whether their responses were correct or not, but also to which category each of the stimuli

belonged, and the correct sine wave grating was shown to the participants at the same time.

The visuospatial working memory task followed the category learning task. The gray squares were presented on the screen for 500 ms. Then, four randomly selected gray squares all turned red for 500 ms before disappearing. After this, another gray square turned red (which could be one of the four squares that had changed color from gray to red or it could be a new square), followed by a series of four quickly presented masks. Each mask was a 9 × 9 grid of gray squares, half of which had a red center. The participants were required to determine whether this square had appeared before or not. If they believed that it had been presented before, they pressed the "F" key. If they believed that it had not been presented before, they pressed the "J" key. After the responses were given, the participants were provided with feedback for 800 ms about whether they were right or wrong. In contrast, the control group was not presented with the visuospatial working memory task. They were required to only perform the category learning task, which was the same as for the experimental group.

# **Results**

# Visuospatial Working Memory Task Performance

The mean accuracy rates averaged across participants were analyzed. The average accuracy of the visuospatial working memory task in the RB-V group was 0.71 ( $\pm$ 0.18), and that of the participants in the II-V group was 0.71 ( $\pm$ 0.17). An independent-samples t-test showed that there was no significant difference between the two groups, t(38) = -0.097, p = 0.977, indicating that there was no difference in the degree of cognitive resources consumed by participants in the RB group and II group when performing the visuospatial working memory task.

## Analysis of the Overall Results

We conducted a 2 (category structure)  $\times$  2 (condition)  $\times$  4 (block) mixed design analysis of variance. This revealed a main effect of block, F(3,225) = 57.28, p < 0.001,  $\eta_p^2 = 0.43$ , indicating learning, and a main effect of condition, F(1,75) = 4.24, p = 0.043,  $\eta_p^2 = 0.05$ , indicating superior accuracy overall for the control condition compared to the visuospatial working memory condition. There was no main effect of category structure, F < 1, and no significant interactions between block and category structure, F(3,225) = 1.37, p = 0.253, between block and condition, F(3,225) = 1.27, p = 0.287, or between category structure and condition, F(1,94) = 1.42, p = 0.237. However, there were significant interactions between block, category structure, and condition, F(3,225) = 4.53, p = 0.004,  $\eta_p^2 = 0.06$ . The interactions with category structure indicate that the condition had a greater effect on RB learning than II learning and that this difference increased across the blocks (**Figure 3**).

Furthermore, for the RB category structure, a 2 (condition) × 4 (block) repeated-measures analysis of variance was performed (**Table 2**). The results showed that the main effect of the block was significant, F(3,111) = 18.45, p < 0.001,  $\eta_p^2 = 0.33$ , indicating that learning occurred. The significant main effect of the condition, F(1,37) = 4.45, p = 0.042,  $\eta_p^2 = 0.11$ , indicated that the participants' learning was significantly different

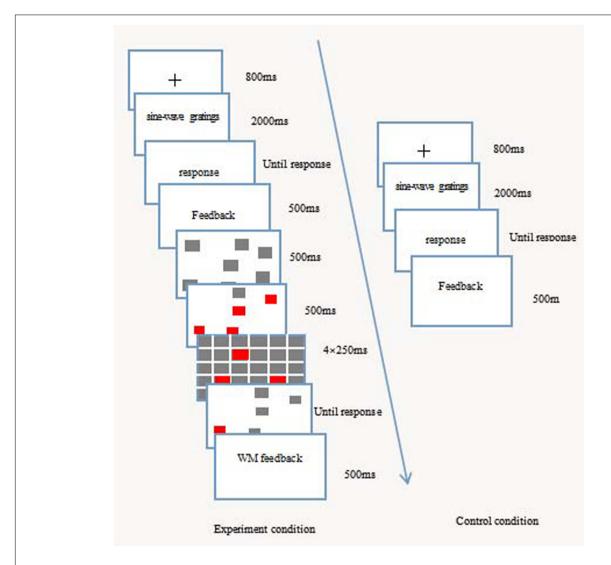


FIGURE 2 | The experimental flow chart of the category learning and visuospatial working memory tasks, under the condition of sequential presentation.

in the different conditions. Furthermore, the interaction between the condition and block was significant, F(3,111) = 4.50, p = 0.005,  $\eta_p^2 = 0.11$ , indicating that, in the two conditions, the findings of the different blocks were significantly different. The analysis of the simple effects showed that the difference in results between the experimental group and control group was not significant in Block 1 (p = 0.553). In Block 2, the results of the RB task categorization of the experimental group were significantly lower than those of the control group (p = 0.050). In Block 3, the results of the categorization task of the experimental group were not significantly different from those of the control group (p = 0.077). In Block 4, the results of the categorization task of the experimental group were significantly lower than those of the control group (p = 0.008) (**Figure 3**). All of these findings indicate that performing the visuospatial working memory task immediately after the feedback impaired the RB category learning.

For the II category structure, the 2 (condition)  $\times$  4 (block) repeated-measures analysis of variance was performed in the same way. The results showed that the main effect of the block was significant, F(3,114) = 43.53, p < 0.001,  $\eta_p^2 = 0.53$ , indicating that learning occurred. The main effect of the condition was not significant, F(1,38) = 0.46, p = 0.503, and the interaction between the condition and block was not significant, F(3,111) = 0.75, p = 0.525 (**Figure 3**). All of these findings indicate that the visuospatial working memory task conducted immediately after the feedback did not influence the II category

To summarize, we found that a visuospatial working memory task interferes with RB but not II category learning when the dual-task experimental paradigm with sequential presentation is used. The significant effect of visuospatial working memory on RB category learning replicates the effect observed in Maddox et al. (2004) with a verbal working memory task, and extends

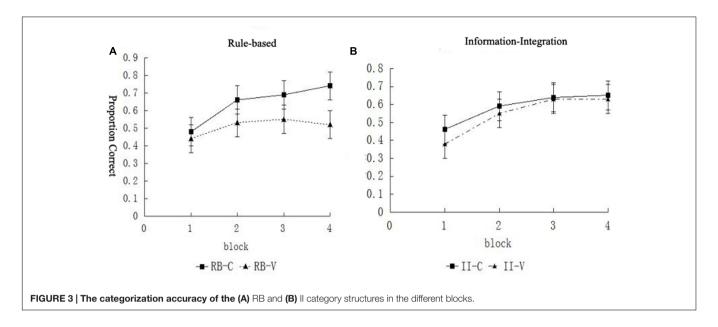


TABLE 2 | Effects of working memory on the II and RB category structures ( $M \pm SD$ ).

	1	2	3	4
RB-C	$0.48 \pm 0.18$	$0.66 \pm 0.22$	$0.69 \pm 0.25$	0.74 ± 0.25
RB-V	$0.44 \pm 0.16$	$0.53 \pm 0.20$	$0.55 \pm 0.23$	$0.52 \pm 0.24$
II-C	$0.46 \pm 0.14$	$0.59 \pm 0.18$	$0.64 \pm 0.22$	$0.65 \pm 0.20$
II-V	$0.38 \pm 0.18$	$0.55 \pm 0.17$	$0.63 \pm 0.18$	$0.63 \pm 0.20$

RB and II represent the ule-based category structure and the information-integration category structure, respectively. RB-C represents the rule-based category structure control group, RB-V represents the rule-based category structure experimental group, II-C represents the information-integration Category structure control group, and II-V represents the information-integration category structure experimental group. The numbers 1, 2, 3, and 4 represent the four blocks of the learning process.

the effect to a visuospatial working memory task. As outlined in the introduction, the RB learning involves generating a representation of the stimulus, response, and feedback. Thus, placing a load on a separate visuospatial working memory store will affect the feedback processes. In contrast, the II category learning appears to occur incrementally in a fashion that is heavily dependent on immediate feedback. As such, would a nested form of visual working memory affect category learning? In Experiment 2, we used an embedded paradigm in which the category learning task was embedded in the visuospatial working memory task in order to examine the effect of the working memory on RB and II category learning.

# **EXPERIMENT 2**

# **Materials and Methods**

## **Participants**

We randomly selected 87 students (40 male, 47 female) who were participating in the secondary post-graduate examination held by the education school of Guangzhou University. The average age was 19.61 years (±1.62). Twenty participants were assigned to the RB-C condition, 24 to the RB-V condition, and 22 and 21 to the II-V condition and the II-C condition, respectively. We aimed for 20 participants per condition based on previous studies, such as Miles and Minda (2011). All of the participants were right-handed, had normal or corrected-to-normal vision, and had no color blindness or color weakness problems. Written informed consent was obtained from all participants before starting the investigation in accordance with the Declaration of Helsinki, and the study was approved by the ethical committee of Guangzhou University.

# **Experimental Materials**

These were the same as in Experiment 1.

## **Experimental Design**

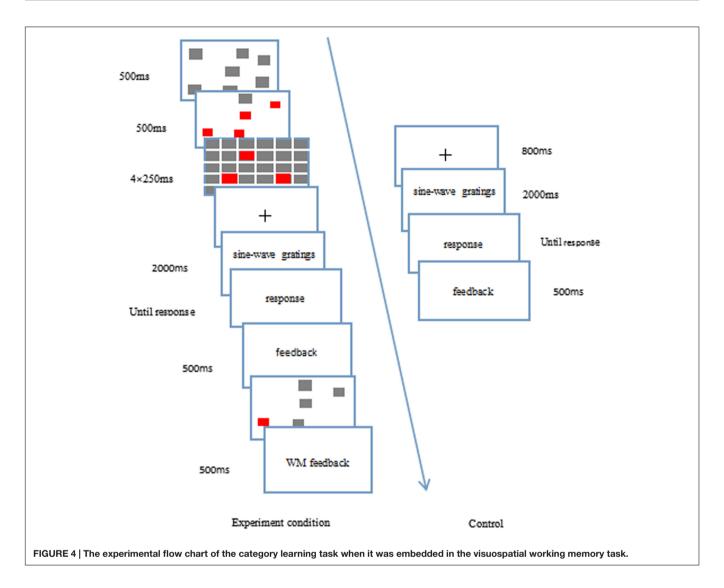
This was the same as in Experiment 1.

#### **Experimental Procedure**

The dual-task experimental paradigm with simultaneous presentation was employed in which the category learning task was integrated into the visuospatial working memory task (**Figure 4**). The whole experimental process was divided into three stages.

In the first stage, the gray squares were presented for 500 ms. Four random squares of the screen then turned red for 500 ms, after which the screen disappeared. The masking appeared four times in sequence, each one lasting for 250 ms (1000 ms in total), in which random flickering squares were presented on each screen. The participants did not have to respond during this stage.

The second stage was the category learning task. A fixation cross (i.e., a "+") was presented for 800 ms, after which it disappeared. The screen then showed the RB or II category structure for 200 ms, after which it disappeared, and the response screen of the category learning was presented, in



which there were four categories (i.e., A, B, C, and D). The participants determined which category structure it belonged to and pressed the relevant key on the keyboard for each category (i.e., 1, 2, 3, and 4, respectively). The screen disappeared after the responses were given, and the instant feedback was then provided.

In the third stage, after finishing the category learning task, the gray squares were randomly presented on the screen for 500 ms, followed by the detection screen, in which a gray square turned red (which may have occurred in the first stage or not) and the participants were required to determine whether this square had appeared before or not. If the participant believed that it had been presented before, they pressed the "F" key. If the participant believed that it had not been presented before, they pressed the "J" key. The detection screen disappeared after the responses were given, and the simple feedback was then provided. The whole experimental procedure included four blocks, each of which had 80 trials. If the participant's performance on the visuospatial working memory task in each block was lower than 80%, a warning window popped up at the end of the block. For

the control group, there was no visuospatial working memory task and participants were required to only perform the category learning task, which was the same as for the experimental group.

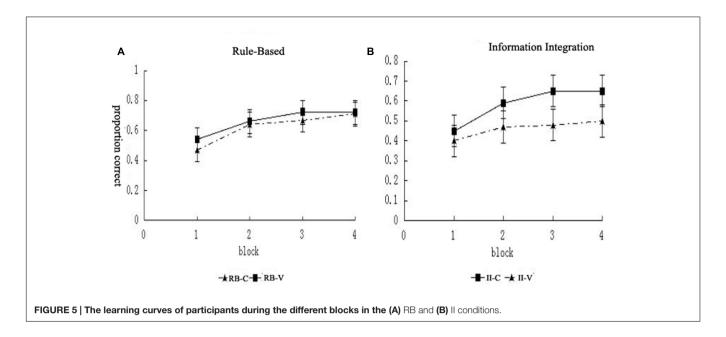
## Results

#### Concurrent Task Performance

The average accuracy for the visuospatial working memory task of participants in the RB-V group was 0.72 ( $\pm$ 0.15), and that of participants in the II-V group was 0.68 ( $\pm$ 0.11). An independent-samples t-test showed that there was no significant difference between the two groups, t(44) = -0.943, p = 0.320, indicating that there was not a difference in the degree of cognitive resources consumed by participants in the RB and II groups when performing the visuospatial working memory task.

# Analysis of the Category Learning

We conducted a 2 (category structure)  $\times$  2 (condition)  $\times$  4 (block) mixed design analysis of variance. This revealed a main effect of block, F(3,249) = 62.33, p < 0.001,  $\eta_p^2 = 0.43$ , indicating learning, and a main effect of category structure, F(1,83) = 8.98,



p = 0.004,  $\eta_p^2 = 0.10$ , indicating superior accuracy overall for the RB category structure compared to the II category structure. There was no main effect of condition, F(1,83) = 1.20, p = 0.276, and no significant interactions between block and category structure, F(3,249) = 2.26, p = 0.082, or between block, category structure, and condition, F < 1. However, there were significant interactions between block and condition, F(3,249) = 2.90, p = 0.036,  $\eta_p^2 = 0.03$  and between category structure and condition, F(1,83) = 3.99, p = 0.049 (**Figure 5**).

Furthermore, for the RB category structure, we performed a 2 (condition) × 4 (block) repeated-measures analysis of variance (Table 3). The results showed that the main effect of the block was significant, F(3,126) = 34.36, p < 0.001,  $\eta_p^2 = 0.45$ , indicating the existence of a learning effect. The main effect of the condition was not significant, F(1,42) = 0.33, p = 0.567. In addition, the interaction between the condition and block was not significant, F(3,126) = 0.81, p = 0.493. All of these findings indicate that the visuospatial working memory task did not affect the RB category learning.

For the II structure, the 2 (condition)  $\times$  4 (block) repeatedmeasures analysis of variance showed that the main effect of the block was significant, F(3,123) = 29.07, p < 0.001,  $\eta_p^2 = 0.42$ , indicating the existence of a learning effect. The main effect of the condition was significant, F(1,41) = 6.17, p = 0.017,

TABLE 3 | Effects of visuospatial working memory on the II and RB category structures under the condition of simultaneous presentation  $(M \pm SD)$ 

	1	2	3	4
RB-C	$0.47 \pm 0.18$	$0.64 \pm 0.22$	$0.67 \pm 0.26$	0.71 ± 0.27
RB-V	$0.54 \pm 0.16$	$0.66 \pm 0.23$	$0.72 \pm 0.23$	$0.72 \pm 0.23$
II-C	$0.45 \pm 0.14$	$0.59 \pm 0.18$	$0.65 \pm 0.21$	$0.65 \pm 0.20$
II-V	$0.40 \pm 0.14$	$0.47 \pm 0.17$	$0.48 \pm 0.17$	$0.50 \pm 0.20$

 $\eta_p^2 = 0.11$ , as was the interaction between the condition and block, F(3,123) = 4.03, p = 0.009,  $\eta_p^2 = 0.09$ , indicating that in these two conditions, the results of the different blocks were significantly different.

In order to further investigate the interaction between the conditions and blocks in detail, an analysis of the simple effects was conducted. The results showed that, in Block 1, there was no significant difference in the results between the II-C and II-V groups, p = 0.200; in Block 2, the results of the II-C group were significantly higher than those of the II-V group, p = 0.027; in Block 3, the results of the II-C group were significantly higher those of the II-V group, p = 0.008; and in Block 4, the results of the II-C group were significantly higher than those of the II-V group, p = 0.015 (**Figure 5**).

In Experiment 2, the dual-task paradigm with simultaneous presentation was used, in which the categorization task was integrated into the working memory task. The results indicated that visuospatial working memory affects the II category learning but not the RB category learning. On the contrary, the RB category learning was impaired by the visuospatial working memory task in Experiment 1. Due to there being a similar visuospatial working memory task, the two studies should have found the same effect of the visuospatial working memory task on RB and II category learning (according to the COVIS model, the study results are only affected by the degree of working memory load). Yet, the results of Study 2 showed different patterns of interference with the II category learning and RB category learning compared to the results of Study 1. These results are not explained by the COVIS model. However, Studies 1 and 2 differed in the location of the working memory task. We infer that the visuospatial resource may interfere with the perception of the stimuli. Experiment 2 provides the first piece of evidence that visuospatial working memory affects II category learning. This observed effect is consistent with Zeithamova and Maddox's (2007) hypothesis of the stages of cognitive processing.

# **EXPERIMENT 3**

# **Materials and Methods**

#### **Participants**

We randomly selected 67 students (33 male, 34 female) who were participating in the secondary post-graduate examination held by the education school of Guangzhou University. The average age was 18.98 years ( $\pm 0.79$ ). There were 20 participants assigned to the RB-C condition, 23 to the RB-V condition, and 24 and 23 to the II-V condition and the II-C condition, respectively. All of the participants were right-handed, had normal or correctedto-normal vision, and had no color blindness or color weakness problems. Written informed consent was obtained from all participants before starting the investigation in accordance with the Declaration of Helsinki, and the study was approved by the ethical committee of Guangzhou University.

#### **Experimental Materials**

These were the same as in Experiment 1.

# **Experimental Design**

This was the same as in Experiment 1.

### **Experimental Procedure**

The dual-task experimental paradigm with simultaneous presentation was adopted for the visuospatial working memory experimental group, in which visuospatial working memory was integrated into the category learning. The whole experimental procedure was divided into three stages (Figure 6).

In the first stage, the fixation cross (i.e., a "+") was presented for 800 ms, after which it disappeared. The screen then showed the RB or II category structure for 200 ms, after which it disappeared. During this stage, the participants were not required to respond.

The second stage included the visuospatial working memory task. The gray squares were randomly presented on the screen for 500 ms. Four random squares then changed color from gray to red, which lasted for 500 ms, after which the screen disappeared. The masking appeared four times in a row, with each lasting for 250 ms. After that, the detection screen was presented in which a gray square turned red (which may have appeared before or not) and the participants were required to determine whether this square had appeared before or not. If they believed that it had been presented before, the "F" key was pressed; otherwise, the "J" key was pressed. As soon as the responses were given, the detection screen disappeared, and the feedback about whether the participants were right or wrong was provided.

In the third stage, at the end of the visuospatial working memory task, the response screen of the category learning task was presented, in which there were four categories (i.e., A, B, C, and D). The participants decided to which category structure it belonged, and pressed the counterpart key on the keyboard (i.e., 1, 2, 3, and 4, respectively). The screen disappeared after the responses were given, and abundant feedback was provided instantly. The experimental procedure included four blocks, each of which had 80 trials. For the control group, there was no visuospatial working memory task, and participants were

required to only perform the category learning task. There was a delay of 3000 ms (the shortest presentation time in the whole visuospatial working memory task) for the gray screen between the screen presenting the category structure and the response screen, so that it was the same as for the conditions of the experimental group. The category learning task of the control group was the same as that of the experimental group (Figure 6).

# Results

#### Concurrent Task Performance

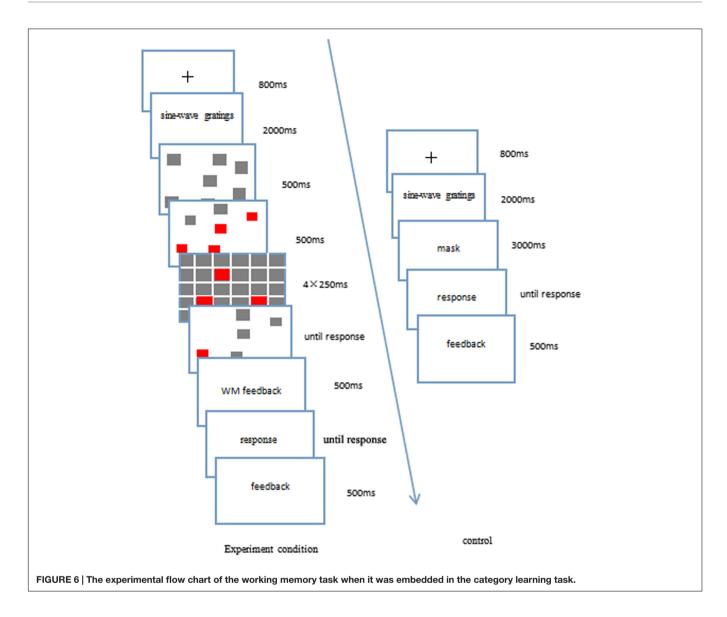
The average accuracy of accomplishing the visuospatial working memory task of participants in the RB-V group was 0.84 ( $\pm$ 0.14), and that of participants in the II-V group was 0.88 ( $\pm 0.09$ ). An independent-samples t-test showed that there was no significant difference between the two groups, t(45) = 1.16, p = 0.167, indicating that there was not a difference in the degree of cognitive resources consumed by participants in the RB and II groups when performing the visuospatial working memory task.

# Analysis of the Overall Results for the Category Learning

We conducted a 2 (category structure)  $\times$  2 (condition)  $\times$  4 (block) mixed design analysis of variance. This revealed a main effect of block, F(3,258) = 74.76, p < 0.001,  $\eta_p^2 = 0.47$ , indicating learning, and a main effect of condition, F(1,86) = 14.52, p < 0.001,  $\eta_p^2 = 0.14$ , indicating superior accuracy overall for the control condition compared to the visuospatial working memory condition. There was no main effect of category structure, F < 1, and no significant interactions between block and category structure, F < 1, between block and condition, F(3,258) = 1.44, p = 0.232, between category structure and condition, F < 1, or between block, category structure, and condition, F(3,258) = 1.13, p = 0.336 (**Figure 7**).

Furthermore, for the RB category structure, we performed a 2 (condition)  $\times$  4 (block) repeated-measures analysis of variance (Table 4). The results showed that the main effect of the block was significant, F(3,123) = 25.36, p < 0.001,  $\eta_p^2 = 0.38$ , indicating the existence of a learning effect. The main effect of the condition was also significant, F(1,41) = 7.87, p = 0.008,  $\eta_p^2 = 0.16$ ; the categorization results of participants in the RB-V group were significantly lower than those of participants in the RB-C group. In addition, the interaction between the condition and block was not significant, F(3,123) = 1.76, p = 0.158. The results showed that the visuospatial working memory task impaired the learning performance in the RB category structure.

For the II category structure, we also performed a 2 (condition) × 4 (block) repeated-measures analysis of variance. The results showed that the main effect of the block was significant, indicating the existence of a learning effect, F(3,135) = 58.41, p < 0.001,  $\eta_p^2 = 0.57$ . In addition, the main effect of the condition was significant, F(1,45) = 6.49, p = 0.014,  $\eta_p^2 = 0.13$ , indicating that the results of participants in the II-C group were significantly higher than those of participants in the II-V group. These findings suggest that the visuospatial working memory task can similarly affect the learning of the II category structure. The interaction between the condition and block was not significant, F(3,135) = 0.31, p = 0.817.



In Experiment 3, the dual-task paradigm with simultaneous presentation was employed, in which visuospatial working memory was integrated into the category learning task. The results revealed that visuospatial working memory interferes with both RB and II category learning, which means that any visual working memory task that involves visual resources, such as the one used in Experiment 2, also disrupts the II category learning system. This finding help to clarify the workings of the implicit system. This system could certainly be a procedural system but it could also rely heavily on visual resources to learn how to classify visually similar stimuli into the same category.

# **GENERAL DISCUSSION**

Previous research has made clear the importance of working memory for RB categories (Zeithamova and Maddox, 2006, 2007; DeCaro et al., 2008; Minda et al., 2008; Rabi et al., 2015). We were interested in further exploring the effect of visuospatial working memory on RB and II category learning, especially investigating the role of visual processing and executive functioning. In Experiment 1, the dual-task paradigm with sequential presentation was adopted to investigate the influence of visuospatial working memory on implicit and explicit category learning. The results showed that visuospatial working memory interferes with RB but not II category learning. In Experiment 2, the dual-task paradigm with simultaneous presentation was used, in which the categorization task was integrated into the working memory task. The results indicated that visuospatial working memory affects II category learning but not the RB learning system. In Experiment 3, the dual-task paradigm with simultaneous presentation was employed, in which visuospatial working memory was integrated into the category learning task. The results revealed that visuospatial working memory interferes with both RB and II category learning. Through these three experiments, we found that, regarding the RB category structure, executive function is the main mechanism by which visuospatial

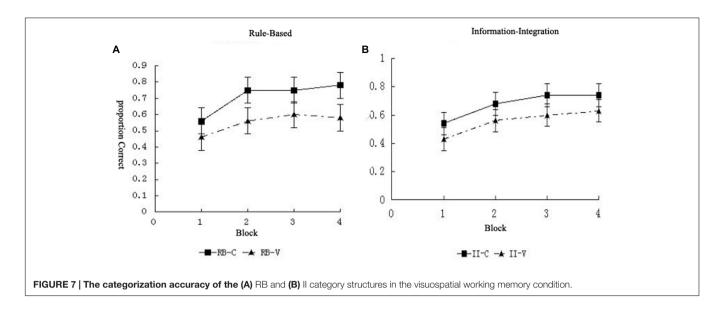


TABLE 4 | Effects of working memory on the II and RB category structures under the condition of simultaneous presentation ( $M \pm SD$ ).

	1	2	3	4
RB-C	$0.56 \pm 0.16$	$0.75 \pm 0.17$	$0.75 \pm 0.17$	$0.78 \pm 0.19$
RB-V	$0.46 \pm 0.16$	$0.56 \pm 0.21$	$0.60 \pm 0.25$	$0.58 \pm 0.27$
II-C	$0.54 \pm 0.12$	$0.68 \pm 0.16$	$0.74 \pm 0.16$	$0.74 \pm 0.15$
II-V	$0.43 \pm 0.14$	$0.56 \pm 0.19$	$0.60 \pm 0.22$	$0.63 \pm 0.22$

RB and II represent the rule-based category structure and the informationintegration category structure, respectively. RB-C represents the rule-based category structure control group. RB-V represents the rule-based category structure experimental group, II-C represents the information-integration category structure control group, and II-V represents the information-integration category structure experimental group. The numbers 1, 2, 3, and 4 represent the four blocks of the learning process.

working memory influences the rules and the discovery of the rules but not the category representation. In addition, regarding the II category structure, visual processing mainly operates on the category representation, which interferes with the connection between the interference space and the specific action.

# **Visuospatial Working Memory Affects** the RB Category Learning

Our study showed that visuospatial working memory affects the RB category learning, and that working memory plays an important role during this process. During the process of the RB category learning, working memory is used to update and retrieve the rules from memory that are tested by feedback, while executive function is also needed to restrain the interference of irrelevant dimensions. Presenting the visuospatial working memory tasks sequentially occupies working memory and, as a result, the verification of rules conducted by the feedback is interfered with (Zeithamova and Maddox, 2007; Grimm and Maddox, 2013). When the visuospatial working memory task was embedded in the category learning (as in Experiment 3), we believe that the visuospatial working memory task mainly interfered in the discovery of the categorization rules; as soon as the participants were successful in identifying the categorization rules, they were able to learn successfully and their accuracy increased significantly.

However, when the category learning task was embedded in the visuospatial working memory task, the results showed that the effect of visuospatial working memory on RB category learning disappeared. That is, visuospatial working memory did not affect the RB category structure. It is worth noting that, although they are both task paradigms with simultaneous presentation, the existing studies suggest that, compared with the condition in which the visuospatial working memory task is integrated into the category learning task (as in Experiment 3), the condition in which the category learning task is integrated into the visuospatial working memory task requires a higher level of executive function. This is because, during the process of accomplishing the category learning task, participants need to use working memory consistently to retain the beginning of the visuospatial working memory task (Miles and Minda, 2011).

Therefore, according to the assumption of the COVIS model, the RB category learning should be hindered more heavily when the category learning task is integrated into the visuospatial working memory task than when the visuospatial working memory task is integrated into the category learning task. However, our experimental results contradicted this. Why was there such a result? We think that this was caused by the fact that working memory or executive function can affect a specific phase of cognitive processing during category learning. Although the condition in which the category learning task is integrated into the visuospatial working memory task requires more executive function, in the RB category structure learning, the perception of the category stimuli does not rely on executive function. Zeithamova and Maddox (2007) indicated that visuospatial working memory is more likely to be used to represent the optimal categorization criteria, while during explicit category learning, it uses assumptions to examine the categorization rules and relies on working memory to keep these categorization rules in mind.

# **Visuospatial Working Memory Affects** the II Category Learning

According to the COVIS model, working memory does not affect the learning of the II category structure, because II category learning establishes a connection between a specific perceptual area of the brain and a specific action, relying on the implicit category learning system. However, our results showed that the visuospatial working memory task also affected the RB and II category structure. When simultaneous tasks were used, the executive function of the visuospatial working memory task, no matter whether at a high or low level, affected the results of the II category structure, which indicates that executive function is not the key factor that affects the II category structure, whereas the visual processing of the visuospatial working memory task plays an important role. Dunn et al. (2012) found that the type of grating mask presented after the category stimuli affected the perceptual representation of the implicit category learning, which to some extent indicates that in the learning of the II category structure, visual processing is more likely to affect the original perceptual representation of the category stimuli. In addition, it has been found that the visuospatial working memory of children is slower than that of adults, but the visual processing capacity of children is fully developed and is not lower than that of adults (Huang-Pollock et al., 2011). Minda et al. (2008) showed that the learning results of children (5-7 years old) for the II category structure was not significantly different from that of adults.

How does visual processing affect the implicit category system? We think that the visual processing of the visuospatial working memory task affects the different processing stages of the category learning. By comparing Experiment 1 with Experiment 3, we can observe that, in the condition of the sequential presentation of the dual tasks, the visuospatial working memory task did not affect the II category structure because the II category learning depends on the connection between a specific area of the brain and a specific action.

The primary role of feedback is to provide instant reinforcement, and this stage of forming the category criterion does not necessarily rely on working memory and visual processing; it is more likely to involve implicit unconscious processing. As a result, the visuospatial working memory task with sequential presentation does not influence the II category learning, whereas when dual tasks with simultaneous presentation are used, the intensity of the executive function when the visuospatial working memory task is integrated into the category learning task is the same as when the tasks are presented sequentially. This indicates that when visuospatial working memory influences the II category structure, it is the location of the visuospatial working memory rather than the intensity of the executive function that is actually operating.

By comparing Experiment 2 with Experiment 3, we can observe that the II-V group is always better than the II-C group, which indicates that presenting the visuospatial working memory task after the II category structure has a negative influence on the category learning results from the very beginning of the learning. This suggests that an individual is more likely to be influenced by visual processing during the stage of category representation.

However, when the category learning was integrated into the visuospatial working memory task, as for the overall learning cycle, there was no significant difference in results between the II-C and II-V groups in Block 1, and the results of the II-V group were significantly higher than those of the control group from Block 2 onward. Visuospatial working memory involves visual processing and visual perception, while the implicit category system needs to project a specific representation to a specific area of the brain and depends on the visual and perceptual memory systems to improve the stimulus representation that has been recognized and processed, especially to distinguish between representations that are similar but not the same. Therefore, when the visuospatial working memory task is presented at the very beginning, it does not affect the process of the representation of stimuli from different category learning phases, but it does affect the establishment of the connection between the perceptual space and the specific action (i.e., it affects the representation of the category criterion).

# CONCLUSION

- (1) Visuospatial working memory affects RB and II category
- (2) Regarding the RB category structure, visuospatial working memory influences the discovery of rules in particular.
- (3) Regarding the II category structure, visual processing primarily operates on the category representation, which interferes with the connection between the perceptual space and the specific action.

### ETHICS STATEMENT

The study was approved by the ethical committee of Guangzhou University. Because the data were analyzed anonymously, and no apparent ethical research complication with participation could be identified, informed oral consent was recommended and obtained from participants before data collection. Participants were given the opportunity to refuse to participate, to omit questions or to withdraw from the study at any time without penalization.

# **AUTHOR CONTRIBUTIONS**

QX and HS conceived and designed experiments. HS carried out experiments and analyzed experimental results. HS and QX wrote the manuscript.

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# **Effect of Redundant Haptic** Information on Task Performance during Visuo-Tactile Task Interruption and Recovery

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Previous studies have revealed that interruption induces disruptive influences on the performance of cognitive tasks. While much research has focused on the use of multimodal channels to reduce the cost of interruption, few studies have utilized haptic information as more than an associative cue. In the present study, we utilized a multimodal task interruption scenario involving the simultaneous presentation of visual information and haptic stimuli in order to investigate how the combined stimuli affect performance on the primary task (cost of interruption). Participants were asked to perform a two-back visuo-tactile task, in which visual and haptic stimuli were presented simultaneously, which was interrupted by a secondary task that also utilized visual and haptic stimuli. Four experimental conditions were evaluated: (1) paired information (visual stimulus + paired haptic stimulus) with interruption; (2) paired information without interruption; (3) nonpaired information (visual stimulus + non-paired haptic stimulus) with interruption; and (4) non-paired information without interruption. Our findings indicate that, within a visuotactile task environment, redundant haptic information may not only increase accuracy on the primary task but also reduce the cost of interruption in terms of accuracy. These results suggest a new way of understanding the task recovery process within a multimodal environment.

Keywords: task interruption and recovery, multitasking, multimodal task, working memory, haptic stimuli

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# INTRODUCTION

In daily life, people face various cognitive tasks, such as sending an e-mail or entering data into a computer in their workspace or home. Usually, these tasks are quite simple and completed with no errors. However, people often encounter circumstances in which another unexpected task interrupts the execution of the prior task. In practice, interruptions between multiple cognitive tasks occur frequently, and researchers have investigated these shifts in attention in workspaces via observational studies (Chisholm et al., 2000; Czerwinski et al., 2004; González and Mark, 2004). Numerous studies have attempted to identify how interruptions affect tasks and how people resume their original tasks after interruptions within a typical workspace (Czerwinski et al., 2004; Mark et al., 2005; Iqbal and Horvitz, 2007). For instance, a ring tone from a phone call, the arrival of a new e-mail, or a question from a colleague can all represent external interruptions that occur while performing a primary task that engages a person's attention (examples given by Fisher, 1998). With

Haptic Information in Task Interruption

advanced technology, the number of complex situations and potential interruptions that divide people's attention has rapidly increased.

Recently, psychologists and human-computer interaction researchers have begun to focus on understanding the role of interruptions in cognitive control. A number of studies have revealed that interruptions are disruptive: Interruption by a secondary task causes interference in performing the primary task. Baddeley et al. (1984) demonstrated concurrent decreases in performance on two simultaneous tasks that require cognitive resources and therefore use working memory. Recent studies also focused on what makes interruptions disruptive, confirming this in two ways. Firstly, resuming the primary task requires more time following an interruption, a phenomenon referred to as resumption lag (Hodgetts and Jones, 2006; Monk et al., 2008; Brumby et al., 2013). In addition, interruptions lead to an increase in the likelihood of errors within the recovered task (Trafton et al., 2011; Brumby et al., 2013). These two prominent influences are common within different kinds of tasks, such as simple data-entry tasks (Zish and Trafton, 2014), sequential tasks (Trafton et al., 2011), cognitively demanding tasks (Borst et al., 2015), and decision-making tasks (Gathmann et al., 2015). Research in the field of human-computer interaction has also examined task switching and cognitive control in order to predict human task performance (Hornof et al., 2010). In addition, task switching has been noted for its effects on performance and mental load in both single-modal (Bailey et al., 2001) and multimodal user interfaces (Lu et al., 2013).

In order to make a precise prediction of performance on novel tasks, researchers have endeavored to elucidate the entire cognitive recovery process. Working memory is utilized for the maintenance and processing of information in the task at hand (Barrouillet et al., 2011) and is considered crucial for shifting cognitive tasks (Drews and Musters, 2015). Barrouillet et al. (2004) proposed a model of time-based resource management with regard to the maintenance and processing aspects of working memory. According to this model, information associated with the current task can undergo a decay process when attention toward the task is switched. In addition, task switching results in decreased recall performance (Liefooghe et al., 2008).

When people are faced with a situation in which their primary task is interrupted by a secondary task, information regarding the primary task is stored in working memory until resumption of the task following completion of the secondary task (Trafton et al., 2003). This ability to multitask is a common capability that allows most people to deal with interruptions without grave hardship. However, due to the limited capacity of working memory, the new information relevant to the secondary task can interfere with the information related to the primary task (Drews and Musters, 2015). The storage capacity of working memory has been researched for decades, and it is now wellknown that the central capacity is limited to a few chunks of

Abbreviations: ANOVA, Analysis of variance; MFG, Memory-For-Goals; Hp, paired haptic stimuli; Hn non-paired haptic stimuli; Ip, interruption present; Ia, interruption absent.

information at a time (Cowan, 2001). Beyond the central capacity (i.e., shared memory capacity for several modalities), Saults and Cowan (2007) revealed the capacity of the peripheral memory for specific modalities (e.g., visual or auditory modality). As each modality has its own peripheral resources, humans can recall more information when both central and peripheral memory systems of different modalities are involved (Cowan et al., 2014).

The Memory-For-Goals (MFG) theory represents one of the most popular frameworks for conveying the effect of interruptions (Altmann and Trafton, 2002). The MFG theory states that the interruption and recovery processes are based on the idea that human memory has a required activation level for each task and its associated goal. Like the working memory model proposed by Barrouillet et al. (2004), the MFG theory asserts that activation associated with a cognitive task decays over time (Altmann and Trafton, 2002). Borst et al. (2015) also specified the interruption and recovery processes in terms of information transference between the problem state and declarative memory. The problem state is a resource that stores requisite information for performing a cognitive task. When a primary task is interrupted, the existing information in the problem state moves to declarative memory, and novel information associated with the interrupting task becomes stored in the problem state. After transference to declarative memory, information associated with the primary task decays over time in terms of a power function (Borst et al., 2015). In addition, the interrupting task increases its own activation level, which produces increased interference on the primary task (Altmann and Trafton, 2002). Several studies have supported this MFG framework, revealing that, when participants are interrupted such that they are required to perform a longer task, increases in resumption lag and the number of errors are observed (Hodgetts and Jones, 2006; Monk et al., 2008; Brumby et al., 2013; Altmann et al., 2014; Borst et al., 2015).

A large proportion of studies have conducted simple visual tasks in laboratory environments using monitors, whereas relatively few studies have utilized a multi-sensory task environment. As real-world tasks occur under multi-sensory circumstances, the recovery process should be studied within multimodal task environment. Hodgetts et al. (2014) and Keus van de Poll and Sörqvist (2016) focused on the auditory modality and investigated the effects of auditory distraction on a visual task recovery. Hodgetts et al. (2014) implemented a command and control task interrupted by yes/no questionnaires with auditory noise. Keus van de Poll and Sörqvist (2016) utilized a writing task interrupted by arithmetic problems with background speech. The results of both studies indicated that the interruption recovery process in a visual modality is affected by distraction from an auditory modality.

Haptic sensation is another less-studied modality involved in multimodal interruption recovery processes. Haptic feedback has been applied in various fields such as remote surgery (Prattichizzo et al., 2012), in-car messaging (Ardoin and Ferris, 2016), and virtual reality (Corbett et al., 2016). For example, Corbett et al. (2016) demonstrated that haptic feedback enhances users' performance in a virtual pointing task. Nam et al. (2008) further revealed that realistic haptic feedback regarding

the movement of the puck and stick improves performance during a virtual air hockey game. Furthermore, the presence of haptic feedback increases participant immersion in a virtual surgery environment (Meijden and Schijven, 2009). However, these studies do not explain the effects of redundant haptic information during multimodal task interruption and recovery. As haptic information is always perceived naturally during our daily cognitive tasks, it is important to understand the precise cognitive processes underlying the influence of this complex modality.

Studies of multimodal task interruption have utilized haptic sensation as an associative cue in order to enhance the activation of the primary task (Hopp et al., 2005; Prewett et al., 2012). When an associative cue and a primary task occur simultaneously, a link between the two is generated, allowing activation of the primary task following the presentation of the associative cue (Altmann and Trafton, 2002). Several studies have therefore applied associated cues in order to increase performance during multitasking (Altmann and Trafton, 2004; Hopp et al., 2005; Hodgetts and Jones, 2006; Smith et al., 2009). Furthermore, Prewett et al. (2012) demonstrated that using a vibrotactile cue (which is obviously non-visual) as an alert or message is more effective than using a visual cue when the primary task is visual. The multiple resource theory (Wickens, 2002) supports the effectiveness of vibrotactile cueing in this multitasking scenario. Wickens (2002) suggested that attentional resources from a separate resource pool distinguished by different sensory modalities can be successfully divided in parallel. Within the framework of the multiple resource theory, Hopp et al. (2005) also suggested that vibrotactile cues help alleviate the cost of interruption by reducing reaction time when the primary decision making task is visual.

However, previous studies utilizing simple vibration motors to implement vibrotactile cues have a clear limitation in that only directional or spatial cue information may be provided (Prewett et al., 2012). Thus, more general haptic sensations beyond vibrotactile cueing should be investigated, particularly in multimodal situations.

Though few in number, some studies have indeed utilized dual task situations that included haptic stimuli. Lu et al. (2013) performed a meta-analysis of studies regarding multimodal dual task situations in which a primary visual task was interrupted by secondary tasks of various modalities, including a haptic modality. As previously noted, interruption of a primary visual task with a secondary haptic task resulted in increased performance relative to interruption of a primary visual task with a secondary visual task. The multiple resource theory proposed by Wickens (2002) may account for such a result. However, in real-world situations, both the primary and secondary tasks rely on multiple modalities. Among various possible combinations of multiple modalities, we aimed to focus on the combination of visual and haptic modalities (visuo-tactile primary task + visuo-tactile secondary task).

In the present study, we implemented a combined visuotactile task in order to investigate the effect of redundant haptic stimuli during a task interruption situation. We first investigated the effect of redundant haptic information on the primary task. Our results align with those obtained by Lu et al. (2013), who studied the effect of redundant auditory information, which has been shown to increase accuracy as well as reaction time during task performance. We then studied the role of haptic stimuli in the interruption recovery process. Specifically, we analyzed how the combined information from paired visual and haptic modalities affects the recovery process relative to non-paired visual and haptic information. Based on the MFG theory, we speculate that priming from the redundant haptic stimulus may exert beneficial effects on the task recovery process. In this paper, we define "task recovery" as the retrieving process of a primary task information after the primary task is distracted by an interrupting task. As few studies have examined this topic, we addressed the following research questions:

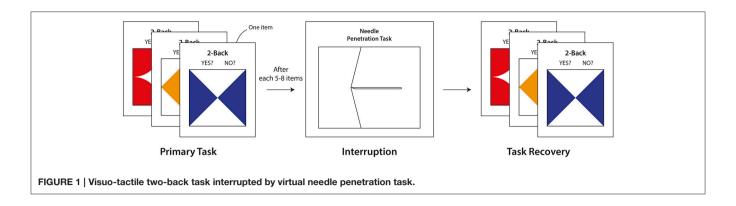
- Q1: Does the cost of task interruption fit the MFG theory in a visuo-tactile task environment?
- Q2: How does the presence of redundant haptic information affect performance in a visuo-tactile cognitive task?
- Q3: Is there any benefit of using redundant haptic information, especially in a visuo-tactile task interruption and recovery process?

#### MATERIALS AND METHODS

Our experiment was characterized by a 2 (Interruption: present vs. absent)  $\times$  2 (Haptic Information: paired vs. non-paired) within-subject factorial design. Therefore, four experimental conditions were used: the two-back visuo-tactile task with paired haptic stimuli (Hp), with and without interruption, and the same two-back task with non-paired haptic stimuli (Hn), also with and without interruption. To create a visuo-tactile task environment that included haptic stimuli, a seven degree-offreedom haptic device was used in conjunction with a PC, monitor, and keyboard.

# **Participant**

Twenty-one students from Yonsei University (14 men; 7 women; age range: 20–26 years, mean age: 22.1  $\pm$  2.36 years) participated in the present study. All participants were righthanded, with no visual or manual impairments, and remained naïve to the purpose of the experiments. No participant had any previous experience with relevant task interruption and recovery experiments. Participants conducted the procedure in a laboratory environment with one experimenter. All individual sessions lasted approximately 1 h. The present study was performed in accordance with the ethical standards laid down by the 1964 Declaration of Helsinki. All study participants provided informed written consent. Following the relevant Act and Enforcement Rules, which are specified below, from the Korean Ministry of Health and Welfare, our experimental procedure is exempt from local ethics committee approval. According to Article 15 (2) of the Bioethics and Safety Act and Article 13 of the Enforcement Rule of Bioethics and Safety Act, a research project "which utilizes a measurement equipment with simple physical contact that does not cause any physical change in the subject" (Korean to English translation by the authors) is exempt from



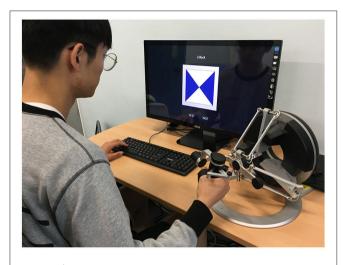


FIGURE 2 | Experimental setup with a haptic device and a PC.

such approval. Our entire experimental procedure was designed to use only a PC and a haptic device that does not cause any physical change in the participant.

# **Materials**

Two kinds of cognitive tasks were used in the present study: a two-back visuo-tactile task and a virtual needle penetration task (Figure 1). Each task was implemented as the primary task and the interrupting task. The primary task (two-back visuo-tactile task) is based upon the N-back design, which is widely utilized for the measurement of working memory in cognitive neuroscience (Kane et al., 2007). Furthermore, this cognitively demanding task has been used to assess the effects of task interruption (Monk et al., 2008; Borst et al., 2015). In order to provide participants with a visuo-tactile experimental environment including precise haptic feedback, our experimental system was composed of one haptic interface (Omega.7, a highly precise force-feedback haptic device with seven degrees-of-freedom produced by Force Dimension, Switzerland) and one PC (Figure 2). A 27-inch display monitor and a keyboard were set up in front of the participant. The haptic device was placed near the dominant hand; because all participants were right-handed, the haptic device was positioned on the right side of the monitor. The haptic

interface can be connected and accessed through the Haptik Library (De Pascale and Prattichizzo, 2007). In addition, both haptic tasks were developed based on CHAI3D, an open-source set of C++ libraries for real-time haptic simulation, and driven with the Windows 8.1 operating system.

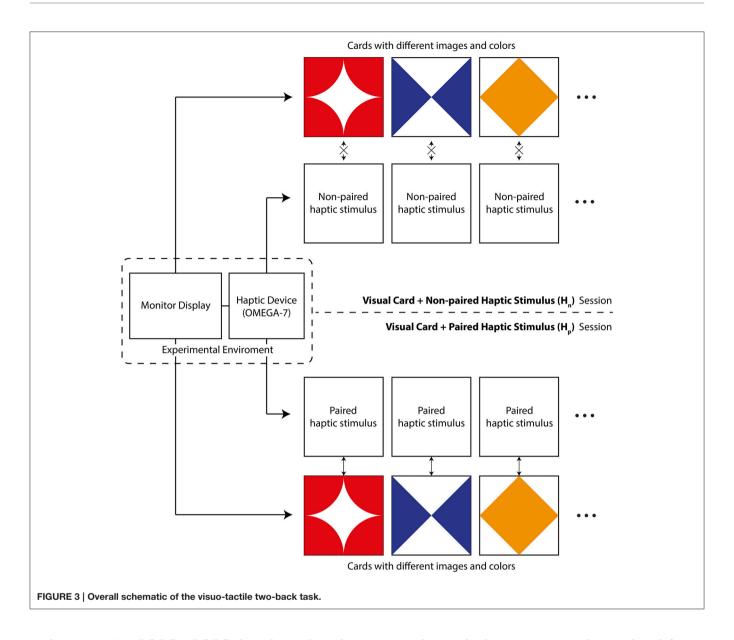
# Two-Back Visuo-Tactile Task (Primary Task)

Participants were asked to perform the two-back visuo-tactile task as the primary task. A stream of visuo-tactile stimuli (cards with visual images and haptic stimuli) were presented sequentially, and participants were required to determine whether the information on the current item was the same as that occurring two items before. Hence, participants were required to keep this information in their working memory while recognizing new information.

In total, nine visuo-tactile stimuli (nine visual cards and nine tactile stimuli occurring in conjunction with one another) were used in the primary task. Since we presented visual and haptic stimuli to a participant at the same time, the information given to the participant was divided into two channels. Figure 3 shows an overall schematic diagram of the two-back visuo-tactile task. First, visual information was provided via a 27-inch monitor as a series of rectangular cards, measuring 5 in  $\times$  5 in (Figure 3). All nine visual cards were distinguishable as nine different images with nine different colors. A haptic device provided haptic stimuli paired with the aforementioned visual cards. Nine haptic stimuli were generated using CHAI3D and the haptic simulation library as follows. Note that these stimuli are more general than the vibrotactile stimulus utilized in previous studies.

- Viscosity: high-viscosity, mid-viscosity, low-viscosity
- Stiffness: high-stiffness, mid-stiffness, low-stiffness
- Vibration: strong-vibration, mid-vibration, weak-vibration

The different visual cards and haptic stimuli were paired with one another and simultaneously presented to the participant in the H<sub>p</sub> session. Each paired item was presented for 2400 ms, followed by a mask of 240 ms. Participants responded to each item by pressing the corresponding key on the keyboard for each answer: "1" or "y" for "Yes" (i.e., the current item is the same as the item that occurred two items before) and "2" or "n" for "No." For participants who were uncomfortable with pressing two distant keys ("y" and "n"), two nearby keys ("1" and "2") were also offered as an alternative option. Each participant chose and



used one option (i.e., "y"/"n" or "1"/"2") depending on his or her preference throughout the whole experiment. If a participant did not respond within the given time (2400 ms), the response was recorded as a failure (i.e., wrong answer).

Two experimental sessions were implemented in order to investigate the effects of paired haptic information: a paired haptic stimulus (H<sub>p</sub>) session and a non-paired haptic stimulus (H<sub>n</sub>) session. In the H<sub>n</sub> session, participants were presented with a non-paired haptic stimulus and a visual card. The non-paired haptic stimulus was arbitrarily chosen for each visual card. Both sessions of the primary task were interrupted every five to eight items (randomly assigned). Each session consisted of five sets, and one set consisted of 60 items.

# Virtual Needle Penetration Task (Interrupting Task)

As an interrupting task, a virtual needle penetration task, which demands cognitive resources from both visual and haptic senses, was implemented. This interrupting task was adapted from a needle insertion simulation toward haptic-rendered soft tissue originally designed by Gerovich et al. (2004) and Prattichizzo et al. (2012).

A participant was instructed to move a virtual needle on the screen using the haptic device, find an invisible vessel inside the visible virtual skin, and place the tip of the needle inside the vessel (Figure 4). Throughout the interrupting task, the participant used only the right hand to manipulate the haptic device to control the virtual needle and also receive force feedback from the haptic device. The force feedback closely simulates the haptic sensation corresponding to the actual act of touching. The location of the invisible vessel was randomly assigned at each trial; however, the intensity of the force feedback at the moment penetrating the vessel was identical. Since the participant had become familiar with the force feedback intensity upon vessel penetration in the training period conducted prior to the actual

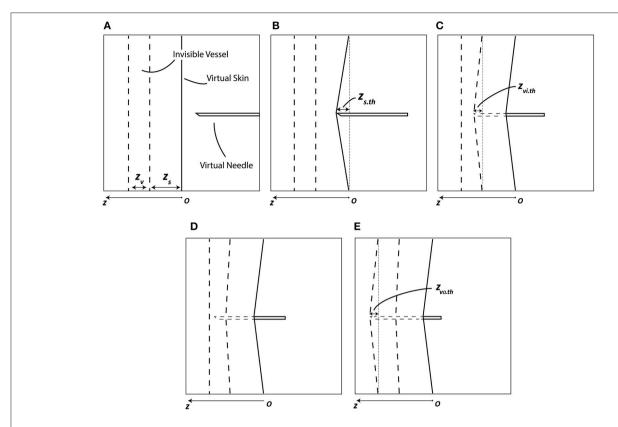


FIGURE 4 | Virtual needle penetration task. The dashed lines in the figure indicate the invisible vessel walls and the invisible part of the needle. The solid lines indicate the visible skin and the visible part of the needle. (A) Before contact. (B) Needle penetrates the skin when  $z > z_{S.th}$ . (C) Needle penetrates the vessel inward when  $z > z_s + z_{vi,th}$ . (D) After successful penetration of vessel. (E) Needle penetrates the vessel outward when  $z > z_s + z_{v} + z_{vo,th}$ ; outward penetration indicates

experiment, the participant with proper concentration could successfully locate the needle inside the vessel. Given a 7200-ms time limit for the interrupting task, a participant was required to use his or her visual sense to penetrate the visible skin and haptic sense to locate the needle inside the vessel. The vessel had a certain thickness, z<sub>v</sub>, and the needle would pass through the other side of the vessel if the participant applied excessive force. When the participant held the tip of the needle inside the vessel for more than 1000 ms without passing through the vessel, the interrupting task successfully terminated.

Adapted from the simulation designed by Gerovich et al. (2004) and Prattichizzo et al. (2012), the following haptic renderings are implemented in this task. Three kinds of soft tissue were generated as virtual renderings of the skin, inward vessel wall, and outward vessel wall. Each layer was assigned distinct spring and damping coefficients. Therefore, participants could be provided haptic feedback such as spring stiffness during contact with the tissue as well as damping effect when the needle passed through any kind of tissue. A detailed haptic model was implemented as follows (based on the haptic model from Gerovich et al. (2004) and Prattichizzo et al. (2012), but simplified by removing some layers and viscous effects).

When the needle contacts and punctures the outermost layer (i.e., virtual skin):

$$F = k_s z, 0 < z < z_{s.th}$$

$$F = b_s z v, z_{s.th} < z < z_s (1)$$

When the needle interacts with the vessel wall, inward-bound:

$$F = k_{vi} (z - z_s) + b_s z_s v, z_s < z < z_s + z_{vi.th}$$
  

$$F = (b_{vi}z + b_s z_s) v, z_s + z_{vi.th} < z < z_s + z_v (2)$$

When the needle interacts with the vessel wall, outward-bound:

$$F = k_{vo} (z - z_v - z_s) + (b_{vi}z_v + b_s z_s) v, \quad z_s + z_v < z < z_s + z_v + z_{vo.th}$$

$$F = (b_{vo}z + b_{vi}z_v + b_s z_s) v, \quad z_s + z_v + z_{vo.th} < z(3)$$

where  $k_s$ ,  $k_{vi}$ , and  $k_{vo}$  represent the spring coefficients of corresponding tissues;  $b_s$ ,  $b_{vi}$ , and  $b_{vo}$  represent the damping coefficients of corresponding layers (per unit thickness);  $z_s$  and  $z_v$ represent the thickness of the outer skin and vessel layers, respectively; and  $z_{s.th}$ ,  $z_{vi.th}$ , and  $z_{vo.th}$  represent the thresholds for penetration shown in Figure 4.

In the interrupting task, the haptic modality was mainly used to determine the vessel's location. Meanwhile, the visual modality was used to monitor the movement of the virtual needle and confirm whether the skin had been penetrated. Unlike in the primary two-back task, the interrupting task was identical in the  $H_p$  and  $H_n$  sessions.

### **Procedure**

Each individual 1-h session was conducted in a laboratory environment. All participants were given a tutorial regarding the experimental procedures, including a clear explanation of the tasks. Prior to the actual experiment, participants engaged in a training session in order to familiarize them with the haptic interface and experimental tasks. The primary two-back task during the training period consisted of 40 Hp (paired haptic stimulus) items and 40 H<sub>n</sub> (non-paired haptic stimulus) items. The goal of the training period was to ensure that participants had become accustomed to the nine visuo-tactile stimulus pairs of the primary two-back task and the force feedback intensity upon vessel penetration during the interrupting task.

After the training period, the actual experiment was conducted. Participants performed five sets of 60 items in each H<sub>p</sub> and H<sub>n</sub> session. Therefore, the entire experiment consisted of 10 sets per person. After every two sets, a participant was given a 3-min break. In order to reduce the potential effect due the order of the tasks, participants were equally divided into two groups; one performed the H<sub>p</sub> session prior to the H<sub>n</sub> session, while the other conducted the  $H_n$  session prior to the  $H_p$  session.

# **Measures**

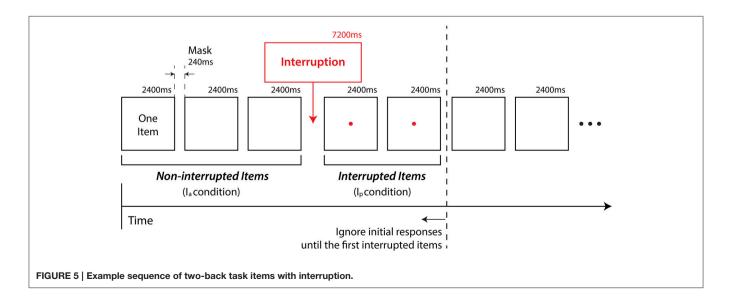
To measure the effects of task interruption in a combined visuo-tactile task environment, we examined reaction time and accuracy as dependent variables. As previously mentioned, increased reaction time and decreased accuracy for the primary task have been highlighted as the major cost of task interruption (Hodgetts and Jones, 2006; Monk et al., 2008; Trafton et al., 2011; Brumby et al., 2013). For every primary two-back task item, the time interval between the moment when a participant received the visuo-tactile stimulus and the moment when the participant pressed the response key was recorded as the reaction time. Each

H<sub>p</sub> or H<sub>n</sub> session consisted of five sets of 60 primary two-back task items, and the average reaction time of each participant for each session was measured. In addition, accuracy was also measured by recording the proportion of correct responses, and the average accuracy of each participant was also recorded for statistical analysis.

Reaction time and accuracy were measured under four conditions: paired haptic stimulus with interruption present (H<sub>p</sub> + I<sub>p</sub>), paired haptic stimulus with interruption absent (H<sub>p</sub> + Ia), non-paired haptic stimulus with interruption present (Hn + I<sub>p</sub>), and non-paired haptic stimulus with interruption absent (H<sub>p</sub> + I<sub>a</sub>). Figure 5 depicts an example sequence of the task items and an interruption. Interruptions occurred at arbitrary points in the sequence. The next two items after an interruption were classified as interrupted items, while other items were classified as non-interrupted items. The performance of interrupted items was recorded as the condition with interruption present  $(I_p)$ . On the other hand, the performance of non-interrupted items was recorded as the condition with interruption absent (Ia). Since initial responses can be extreme outliers (Borst et al., 2015) we also excluded the initial responses until the first interrupted items.

# RESULTS

The cost of interruption recovery can be measured in two ways: reaction time and accuracy. As per the MFG theory, performance of the interrupted task would be degraded in terms of both reaction time and accuracy relative to the non-interrupted task (Altmann and Trafton, 2002; Monk et al., 2008; Altmann et al., 2014). In the present study, we investigated the effects of paired haptic stimulus presentation during interruption recovery. Thus, we first examined whether the haptic stimulus affected the performance of the primary task differently depending on the presence of interruption. Significant interactions between haptic stimulus presentation and the presence of an interruption with regard to accuracy or reaction time indicate that the haptic



stimulus influences the interruption recovery process. As we observed these effects in our analysis, we further analyzed the effects of the haptic stimulus on accuracy. However, we observed no significant interaction between presentation of the haptic stimulus and the presence of interruption with regard to reaction

# **Interactions between Haptic Stimulus** Presentation and the Presence of Interruption on Reaction Time and Accuracy

The interaction between presentation of a haptic stimulus and the presence of interruption can be simply analyzed by examining the haptic benefit depending on the presence of interruption. In the present study, the haptic benefit was defined as an improvement in reaction time or accuracy due to the presence of the paired haptic stimulus (i.e., reaction time or accuracy under H<sub>D</sub> condition minus reaction time or accuracy under H<sub>D</sub> condition). Our analysis based on the subtracted data under two conditions is similar to the approach of Olesen et al. (2004).

We used a paired samples *t*-test to analyze the haptic benefit depending on the presence of interruption. The haptic benefit in terms of reaction time under the interrupted condition was similar to the haptic benefit under the non-interrupted condition (t = 1.526, p = 0.143, Cohen's d = 0.333, according to the 5percent-standard level; non-interrupted task mean = 220.43, SE = 31.11; interrupted task mean = 133.38, SE = 51.69). Thus, we observed no significant interaction between presentation of the haptic stimulus and the presence of interruption with regard to reaction time. In contrast, the haptic benefit in terms of accuracy under the interrupted condition was significantly better than the haptic benefit under the non-interrupted condition (t = -5.640, p < 0.01, Cohen's d = 1.231, according to the 5-percent-standard level; non-interrupted task mean = 0.70, SE = 0.68; interrupted task mean = 8.03, SE = 1.32). Thus, we observed a significant interaction between the presentation of the haptic stimulus and the presence of interruption with regard to accuracy. The same result was obtained by the two-way repeated measures analysis of variance (ANOVA) described in the next section.

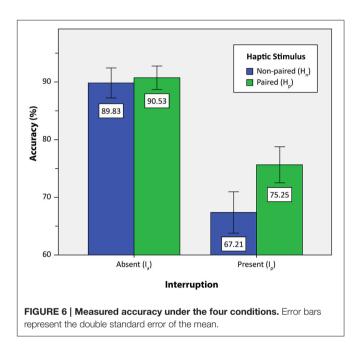
# **Effect of Haptic Stimulus on Accuracy** during Interruption Recovery Process

We measured the accuracy of participants in the primary twoback task under the aforementioned four conditions (i.e., H<sub>p</sub>  $+ I_p$ ,  $H_p + I_a$ ,  $H_n + I_p$ ,  $H_n + I_a$ ). Mean accuracy values for the 21 included participants are presented in Table 1. As we predicted based on the MFG theory, participants made more errors in the interrupted condition than in the non-interrupted condition (90.18 vs. 71.23%, on average). Two-way repeated measures ANOVA were used to discover significant differences among each condition. The presence of paired haptic stimuli and the presence of interruption were used as within-subject factors in the two-way repeated measures ANOVA.

Figure 6 depicts participant accuracy under the four conditions of the present study. When participants were interrupted by the interrupting task, their accuracy on the

TABLE 1 | Accuracy in the primary two-back task.

Condition	Range (%)	Mean (%)	SD (%)	Combined Mean (%)
H <sub>p</sub> +I <sub>p</sub> (Paired Haptic Stimulus, Interrupted)	80.6–97.0	90.47	4.58	90.18
$H_n + I_p$ (Non-paired Haptic Stimulus, Interrupted)	77.4–97.0	89.80	5.83	
H <sub>p</sub> +l <sub>a</sub> (Paired Haptic Stimulus, Non-interrupted)	60.1–88.0	75.17	6.78	71.23
$H_n+I_a$ (Non-paired Haptic Stimulus, Non-interrupted)	48.0–76.0	67.23	8.02	



primary two-back task decreased significantly  $[F_{(1, 20)} = 237.100,$ MSE = 31.801, p < 0.01,  $\eta^2 = 0.922$ ]. In addition, participants achieved significantly better accuracy when paired haptic stimuli were provided than when non-paired haptic stimuli were provided  $[F_{(1, 20)} = 28.122, MSE = 14.254, p < 0.01, \eta^2]$ = 0.584]. Furthermore, we observed a significant interaction between the presentation of a haptic stimulus and the presence of interruption with regard to accuracy, in accordance with our *t*-test results discussed in the previous section  $[F_{(1, 20)} = 31.815,$ MSE = 8.870, p < 0.01,  $\eta^2 = 0.614$ ]. That is, the paired haptic stimulus further enhances accuracy when the task is interrupted relative to when the task is not interrupted.

Our data analysis confirms the following results regarding the effect of paired haptic stimuli on task performance during visuotactile task interruption and the subsequent recovery process: (1) The presence of a paired haptic stimulus improves accuracy on the primary two-back task; (2) the paired haptic stimulus affects the accuracy differently depending on the presence of interruption; the paired haptic stimulus further enhances the accuracy when the interruption is present.

Haptic Information in Task Interruption

# DISCUSSION

Multiple sensory channels have been studied to understand the cognitive processes involved in multimodal task interruption and recovery. Previous studies have focused on visual and auditory modalities in particular, while studies involving haptic stimuli have been limited to an investigation of their role as associative cues in enhancing performance during the primary task. In the present study, we conducted a visuo-tactile task interruption and recovery experiment in order to examine the role of redundant haptic information in such processes. Our results confirm that the use of redundant haptic information enhances participant accuracy on the primary visuo-tactile task. Noticeably, the redundant haptic information is especially helpful for participants to recover the interrupted task. This increase in accuracy is significantly greater during interruption recovery than during a non-interrupted task.

• Q1: Does the cost of task interruption fit the MFG theory in a visuo-tactile task environment?

Our results align with the MFG theory, revealing an increased cost of task interruption with regard to accuracy. Regardless of the haptic stimulus, participants demonstrated decreased accuracy when they were interrupted. Hence, our data support the results of previous studies regarding interruption in a multimodal task environment (Hodgetts et al., 2014; Keus van de Poll and Sörqvist, 2016).

• Q2: How does the presence of redundant haptic information affect performance in a visuo-tactile cognitive task?

Our results indicate that redundant haptic information provided in the form of a paired haptic stimulus induces improvements in accuracy regardless of the presence of interruption. As mentioned earlier, Lu et al. (2013) investigated the use of redundant auditory information, which resulted in improved accuracy on a single visuo-auditory task without interruption. Our results indicated that similar enhancements are observed when redundant haptic information is provided during a visuo-tactile task.

• Q3: Is there any benefit of using redundant haptic information, especially in a visuo-tactile task interruption and recovery

The presence of the paired haptic stimulus resulted in significantly greater improvements in accuracy in the interrupted condition than in the non-interrupted condition, a comparison not studied in Lu et al. (2013). Such a result demonstrates that redundant haptic information exerts a specific influence on the interruption recovery process.

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Similar to performance enhancements observed when associative cues are presented during the recovery process, increases in accuracy due to the presentation of redundant haptic information may be explained as a result of enhanced activation of the primary task, according to the MFG theory (Altmann and Trafton, 2002). An associative cue boosts the activation of the primary task (i.e., priming occurs) due to generation of a link between the cue and the primary task. Likewise, redundant haptic information can boost the activation of the primary task during the recovery process because a similar link between the haptic information and the primary task is generated.

The results of the present study suggest that haptic information may be effective for interruption management. In their meta-analysis, Lu et al. (2013) suggested various ways of using multimodal information for designing efficient multimodal interfaces. For example, haptic modalities can be effectively utilized to deliver low-complexity information such as simple notifications, while auditory modalities can be used to deliver high-complexity information such as informative alerts. However, such suggestions are based on limited experiments that have utilized a vibrotactile motor unable of delivering a complex haptic stimulus. However, the highly precise force feedback haptic device used in the present study is capable of generating highly complex haptic stimuli that can vary in terms of viscosity, stiffness, vibration, magnetic force, various textures, etc. The significant improvements in accuracy observed during the present study demonstrate the ability of haptic stimuli to provide such highly complex information for the management of interruptions. Our results may provide a foundation for elucidating the mechanisms underlying the recovery process in a multimodal sensory environment.

# **AUTHOR CONTRIBUTIONS**

HM and JS designed the study. HM developed the experimental software and performed the experiment. HM, JB, and JS analyzed the data and discussed the results. HM drafted the manuscript, and JB and JS revised the manuscript. All authors approved the final manuscript.

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# Phone Conversation while Processing Information: Chronometric Analysis of Load Effects in Everyday-media Multitasking

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This is a pilot study that examined the effect of cell-phone conversation on cognition using a continuous multitasking paradigm. Current theorizing argues that phone conversation affects behavior (e.g., driving) by interfering at a level of cognitive processes (not peripheral activity) and by implying an attentional-failure account. Within the framework of an intermittent spare-utilized capacity threading model, we examined the effect of aspects of (secondary-task) phone conversation on (primary-task) continuous arithmetic performance, asking whether phone use makes components of automatic and controlled information-processing (i.e., easy vs. hard mental arithmetic) run more slowly, or alternatively, makes processing run less reliably albeit with the same processing speed. The results can be summarized as follows: While neither expecting a text message nor expecting an impending phone call had any detrimental effects on performance, active phone conversation was clearly detrimental to primary-task performance. Crucially, the decrement imposed by secondary-task (conversation) was not due to a constant slowdown but is better be characterized by an occasional breakdown of information processing, which differentially affected automatic and controlled components of primary-task processing. In conclusion, these findings support the notion that phone conversation makes individuals not constantly slower but more vulnerable to commit attention failure, and in this way, hampers stability of (primary-task) information processing.

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# INTRODUCTION

Everyday experience tells us that people have profound multitasking abilities since multitasking activities are extremely common in people's everyday-life routines (cf. Bills, 1943, pp. 151–185; Salvucci and Taatgen, 2011, pp. 3–24). For example, researchers are often talking of running multiple projects concurrently, or are concurrently consuming multiple media sources at work and leisure. Sufficient practice provided, people might even be able to acquire superior everyday-life multitasking abilities (Ophir et al., 2009; Schubert et al., 2015), which is particularly true within the area of multimedia applications and gaming (Strobach et al., 2012). Not surprisingly, since the majority of actions and decisions is governed by routinized programs (Norman and Shallice, 1986; Langner and Eickhoff, 2013), the commonsense view of multitasking would lead one to expect that

seemingly skilled behavior can concurrently be performed with ease, without any considerable impairment in performance (Finley et al., 2014). Thus, multitasking implies an advantage in time saving in the majority of standard situations, which often leads people to neglect the fact that it might also entail a disadvantage in unexpected situations, where rapid adaptations to changes are required (Hockey, 1997; Wickens, 2008; Parmentier, 2014). Taking up these issues, we focused on multitasking-induced performance (un)reliability, examining effects of phone usage on automatic and controlled components of information processing.

# **Empirical Findings: Loading And Distraction Effects**

Current empirical findings on continuous multitasking effects in the applied domain are largely dominated by two lines of research, by experiments on the effect of multitasking on learning and studying (Rohrer and Pashler, 2003; Pashler et al., 2013), and experiments on the effect of cell phone usage during driving (Alm and Nilsson, 1994; Horrey and Wickens, 2006). The experimental design in such applied studies is usually unconstrained, which brings about the benefits of retaining ecological validity (in some cases, at the cost of experimental control). Although there are (on principle) a variety of design options, the most typical experimental set-up found in the empirical literature usually consists of the following essential elements, a primary task which is usually performed in streams of continuous action, and a secondary task which is conceptualized either as a discrete event (e.g., an infrequent probe task) or a distractor such as a phone call (Sanders, 1998, pp. 271-285). The main line of empirical evidence stems from continuous tracking (or serial responding by key pressing) as the primary task and discrete manual or vocal responses to probe stimuli as the secondary task (Pashler, 1998, pp. 298-317). It is usually asked whether the loading/distractor affects primary-task performance, and the research question is mostly of practical relevance (Strayer and Johnston, 2001; Hancock et al., 2003; Strayer and Drews, 2007).

Empirically, there are three main determinants that affect primary task performance in natural contexts, in particular, the temporal predictability and task predictability of the secondary task, and controllability of the entire task ensemble (Sanders, 1998, pp. 330-359). These factors are ubiquitous and occasionally recognized as such (Kalsbeek and Sykes, 1967; Salvucci and Taatgen, 2008; Steinborn and Langner, 2011, 2012; Reissland and Manzey, 2016), albeit not strictly accounted for by the prevalent multiple-resource theory (Wickens, 1980, 1984). Specifically, when probe stimuli (as secondary task) occur at a constant rate within blocks of trials during the primary task, participants know exactly about when they will occur, and thus, are more likely to engage in appropriate processing strategies (Steinborn et al., 2016b). This again goes better when the nature of the secondary task is also constant, since task operations can better be prepared when these features are predictable as compared to when they are not (Kalsbeek and Sykes, 1967; Thomaschke and Dreisbach, 2015). Finally, multitasking depends

greatly on whether individuals are enabled to do it their own way, that is, when they decided their own scheduling, than when they were to follow fixed schedules. For example, experiments reported by Hockey and Earle (2006) demonstrate that control over the regulation of multitask office work has an eminent impact on the way in which fatigue develops in response to demanding work goals (cf. Sanders, 1998, pp. 394-441).

Much of research in the applied domain is devoted to the effects of cell phone use during driving (e.g., Alm and Nilsson, 1994; Horrey and Wickens, 2006; Cooper and Strayer, 2008; Nijboer et al., 2016), and there is no doubt that this issue is of great practical importance and contributes much to a science-based approach to road safety policy (cf. Strayer and Drews, 2007). The essential finding can be summarized such that the use of mobile phones during driving leads to impairments at a purely cognitive (not peripheral) level thus increasing the risk of an accident. Strayer et al. (2003) examined the hypothesis of whether the observed impairment could be attributed to a disengagement of attention from the visual scene. Their results indicated that although an object is fixated, it is not being processed sufficiently (cf. Huestegge and Adam, 2011). In most countries, therefore, placing and receiving a phone call while driving are only allowed via hands-free systems. Yet, recent findings point to a reduction in attention directed toward the driving task even when using hands-free system car kits indicating that the source of interference produced by phone conversation originates not from manual operations related to phone use but from processing information related to conversation (Drews et al., 2008, 2009; Atchley et al., 2011a,b; Bergen et al., 2013).

Our theorizing given in the following section will finally converge toward an integrated spare-utilized capacity threading model as general framework (Kahneman, 1973). Two key aspects are of great importance. First, findings suggest that distraction effects by phone conversation are primarily caused through the cognitive effects of conversation and not (solely) by peripheral activities related to phone use. Second, the evidence delivers clues as to the possibility that phone-related distraction does not arise from a general slowing of relevant information-processing operations necessary for driving, but from an increase in the probability of attentional failure. For example, Casner and Schooler (2015, p. 38) examined vigilancelike phenomena in pilots performing routine tasks, concluding that people do not gradually become fatigued under vigilance conditions but occasionally jump into a rather discrete state of task-unrelated thoughts, or mind-wandering, respectively (Kurzban et al., 2013; Langner and Eickhoff, 2013; Smallwood, 2013; Steinborn et al., 2016b, for related accounts). Such a view of attention failure implies effects on performance variability which requires a theoretical model capable to explain the mechanism underlying performance fluctuations in active sustained-attention (i.e., mental-concentration) tasks (Pieters, 1983, 1985; Van Breukelen et al., 1995; Steinborn and Huestegge, 2016), and a spare-utilized capacity threading model offers a generic and integrated way of talking about performance variability.

# Theoretical Models: Spare-Utilized Capacity Threading

As already mentioned, we examined phone-related interference in active sustained-attention tasks to enable a chronometric approach to study applied-multitasking phenomena<sup>1</sup>. Central to any theorizing on performance speed and variability in active tasks is a distinction between utilized and spare capacity as structural and a continual swing between these processes as dynamic component, referred to as capacity threading. According to Kahneman (1973, 2013), the most generic way to theorize on the energetic regulation of capacity during continuous mental work is to consider information processing as composed of two qualitatively distinct and constantly alternating classes of mechanisms which he termed operating and monitoring (Craik, 1948; Welford, 1959). Both processes serve different purposes (within the same goal area) and are complementary to each other with regard to energetic requirements. This means that it is subjectively more demanding to engage in mental operations than to not engage (i.e., than to keep spare capacity available). A measure of spare capacity is obtained by analyzing the response to an infrequent probe signal, presented to the individual at an unpredictable time during the primary task (cf. Kahneman et al., 1967; Posner and Boies, 1971; Shulman and Greenberg, 1971). By means of this method, it is possible to determine the amount of (utilized) capacity that is deployed to the task at the instant of probe-signal presentation, and a failure to identify or an unusually slow response to the probe-signal indicates that the individual is currently absorbed in the effective mental operations of the task at hand.

Kahneman (1973) argued that as individuals actually engage in the mental operations of the task at hand, spare (fluctuating) capacity is conveyed to utilized capacity and the corresponding increase in task focus would lead to a (temporary) decrease in monitoring. For example, Kahneman et al. (1967) demonstrated that when people engage in highly demanding mental operations (in the add-1 task) for a short period of time (i.e., when they perform a cognitive sprint), they are virtually blind during that period as revealed by measures of the probe-signal technique. In this way, he considered capacity allocation for an impending task as mobilization of mental energy (recruited from available spare capacity) to enable active mental operations. Mobilization

is transient and time-sensitive, which means that it is virtually impossible to voluntarily sustain attention for more than a few seconds within one continuous stream of mental work. From this perspective, sustained attention is considered a mere re-implementation of successive efforts to redirect attention (to retransform spare to utilized capacity) to the task at hand. Thus, even when individuals have the intention to deliberately concentrate on the task for a while, capacity will never fully be utilized at any point during that period, but there is always spare capacity left for monitoring, evaluating, and adjusting pre-set performance standards (cf. Steinborn et al., 2016b).

Such a perspective of spare-utilized capacity threading offers a very natural way to explain variability in active mental tasks where response time (RT) is the primary performance measure. Instead of attributing experimental effects on RT variability to unspecified or umbrella-like terms often used in the literature (e.g., mental noise, ego depletion, lack of motivation, etc.), the model provides a generic and clearly defined mechanism based on spare-utilized capacity threading, according to which variations occur because the allocation policy sometimes channels capacity to other activities, resulting in slower responses during that period of trials (Steinborn et al., 2016b). This directly implies that the RT distribution of an individual is composed of a mixture between two operating mental states, an attentive state and a non-attentive state (cf. Luce, 1986, pp. 273-311; Ulrich and Miller, 1994, pp. 34-36; Van Breukelen et al., 1995, pp. 150-169). In the attentive state, the individual is effectively carrying out mental operations while in non-attentive periods, the individual is not effectively working because utilized capacity is conveyed to spare capacity. Note that this view has some decidedly important properties to explain performance fluctuations beyond mere scaling-variability (Wagenmakers and Brown, 2007), as indicated by relativized indices such as the RT coefficient of variation (RTCV), which is obtained by dividing the intraindividual RT standard deviation by the mean (cf. Steinborn et al., 2016b).

Although the advantage of RT variability and distributional analysis is widely recognized in the basic-research domains, researchers and practitioners in applied-research domains still rely on traditional measures of central tendency. A chronometric approach to studying performance speed and its fluctuation strictly implies a methodology beyond measures of central tendency, which can be studied in a comfortable way by analyzing the cumulative distributive function (CDF) of responses. The reason is that effects on RT mean are not interpretable by itself if they originate from a selective slowing at longer CDF percentiles (Miller, 2006). RT distributions are typically asymmetrical, having a steep slope on the left side (due to a rather narrow range of very fast responses) but an elongated right tail (arising from more broadly distributed slow responses)<sup>2</sup>.

<sup>&</sup>lt;sup>1</sup>In response to a reviewer's comment, we would like to note that it is important to distinguish between active and more passive (i.e., vigilance-like) sustainedattention tasks when theorizing within a spare-utilized capacity threading model (cf. Langner and Eickhoff, 2013). To effectively engage in mental operations (e.g., such as counting, mental addition, or subtraction), the individual has to utilize capacity from available spare capacity, which is termed energetic mobilization (cf. Sanders, 1998, pp. 332–348). In contrast, in rather passive watchkeeping tasks (also referred to as vigilance tests, monitoring task, etc.), the individual's primary task is to wait and watch for relevant targets, and the factor demand is typically increased by lowering target occurrence probability and by increasing negative consequences of missing the target (cf. Broadbent, 1971, pp. 76-111). In this situation, there is no threading between operating and monitoring but a conflict between taskrelated target monitoring and task-unrelated (mind-wandering) tendencies, which are extremely difficult to resolve. The difficulty originates from a basic attentional principle, namely that attention primarily serves action and is to be attained and maintained through acting (cf. Neumann and Prinz, 1987). According to Kahneman (1973, pp. 13-27), it is virtually impossible to mobilize capacity in waitand-watch tasks because they do not require action for most of the time (see also, Casner and Schooler, 2015, for a similar view).

<sup>&</sup>lt;sup>2</sup>Response to a reviewer's comment. As mentioned earlier, the responses of an individual in RT tasks are not symmetrically distributed around the mean but are typically skewed such that they have an elongated tail toward the right. This distributional asymmetry is due to the fact that there is fundamental limit to maximizing response speed but none to response slowing. For example, the classic work of Bills (1931, 1935) devoted particular attention to the occurrence of incidental extra-long responses (which he termed "mental blocks") after periods

Thus, RT variability expresses itself chiefly in responses above RT mean, and many variables affect RT mean only indirectly by selectively affecting stability (cf. Steinborn and Huestegge, 2016; Steinborn et al., 2016b). In the foreground of a research project within a spare–utilized capacity threading model thereby stand the goals of manipulating effort mobilization directly and measuring its effects with high precision by analyzing the entire RT distribution instead of only analyzing RT means (Steinborn et al., 2016a, 2017). This might provide a principal advancement to previous studies in this domain (cf. Sanders, 1998, pp. 394–451).

# **Present Study**

Most work on driver distraction by cell phone conversation focused on the assessment of the impairment rather than on a delineation of the cognitive mechanisms underlying deficits in driving performance. Yet, studies that focused on this question imply an attention-failure account rather than a constant slowing of information-processing activity. In the present study, we aimed to precisely estimate potential impairments of cognitive performance by everyday-life cell phone usage, particularly by talking and texting. Our study can be characterized by two key aspects: First, we used an unconstrained continuous-multitasking paradigm. This is commonly accepted in applied-research domains, however, our approach differs in some way to previous studies since we used self-paced mental arithmetic as primary task, examining performance alone and in combination with unconstrained cell-phone conversation as secondary-task. We decided to use continuous arithmetic in order to enable the application of chronometric methods of RT measurement (Manzey and Lorenz, 1998; Haque and Washington, 2014). Further, we used a naturalistic conversation as secondary task, according to the methodical suggestions of Drews et al. (2008, pp. 393-395), to retain maximal ecological validity (Amado and Ulupinar, 2005; Horrey and Wickens, 2006). Second, in the foreground of our research thereby stands the use of advanced performancemeasurement methodology to critically capture aspects of performance reliability.

Notably though, the bulk of current research on cell-phone distraction neglected this important aspect of measurement. Whether the hypothesized effects on performance originate from

of normal work speed in self-paced color naming. Crucially, it is not a matter of the scale properties (i.e., being finite toward the left but infinite toward the right), as occasionally stated in the literature, but because of a limitation in the speed of processing even when performed with maximum mental efficiency (Steinborn et al., 2016b). To illustrate this, consider a formula-one driver on a particular training day where everything clicks into place (e.g., driver is fully concentrated, check processes occur at exactly the critical moments, team coordination is effective, etc.). On this day, the hypothetical lap times of the driver will be almost always near to ideal line (e.g., 73, 71, 71, 74, 76, 73, 74 s, etc.). Now consider a day where everything is not going as well as it should (e.g., driver not concentrated, team coordination ineffective, etc.). On this day, the driver may likely succeed in some (even in the majority of the) laps but may fail in other ones due to the particular circumstances on this particular day (e.g., 72, 71, 85, 74, 75, 93, 73 s, etc.). Critically, inspecting only measures of central tendency would lead to the conclusion that the driver was simply slower on the bad (vs. the good) day, which is convenient albeit incorrect (or at least incomplete) given that the overall slowing originated from an unfortunate combination of circumstances in some but not all of the rounds yielding extraordinarily slow lap times.

a constant slowing of the speed of information processing, or alternatively, by an increase in the probability of attention failure is fundamental to the analysis and understanding of cell-phone distraction. In order to distinguish between both theoretical alternatives, we need to go beyond traditional measures of central tendency but instead must consider its effect at critical density zones of the entire RT distribution (Balota and Spieler, 1999; Spieler et al., 2000). We computed a CDF for each experimental condition, asking whether phonerelated impairments during continuous cognitive processing makes information processing run more slowly, or alternatively, makes processing run less reliably albeit with the same processing speed. Notably, this distinction is critically implied by current theorizing, albeit not explicitly measured in driving tasks (Groeger, 1999). Consequently, we examined whether experimental effects on RT mean originate from a global slowdown that is equally present at all CDF percentiles (parallel effect) or only from a local effect at slower percentiles (mixture effect). The former would indicate a true influence of continuous information-processing speed while the latter would indicate a destabilization of performance (Steinborn et al., 2016a, 2017).

Globally, we expected to observe an effect of cell-phone conversation on measures of RT and accuracy. That is, responses should be faster and somewhat less erroneous under the single-task condition as compared to a multi-task condition (main effect of context). We further expected faster responses for easy mental arithmetic as compared to hard mental arithmetic (main effect of demand). Whether cell-phone conversation differentially affects easy versus hard mental arithmetic performance is an empirical question, since previous research on continuous multitasking does not deliver enough reliable information on the impact of conversation on automatic versus controlled information processing components (cf. Ashcraft and Battaglia, 1978; Logan, 1979; Borst et al., 2013). To examine behavioral variability, we analyzed both the classic parameters of RT variability and parameters of distributional skewness based on the ex-Gaussian model (cf. Heathcote et al., 1991; Leth-Steensen et al., 2000). Remind that from the perspective of an energetic spare-utilized capacity threading model, it is crucial to know whether cell-phone conversation during cognitive processing leads to a generic (vs. selective) slow-down of all (vs. only long) CDF percentiles. Theorizing within an energetic-capacity framework, conversation is expected to hamper information-processing by increasing the probability of attentional failure. We examined both the effect of expecting and performing phone talking (Experiment 1) and text communication (Experiment 2) on cognitive performance, using the same sample of participants (within the sequence of both experiments counterbalanced across participants).

# MATERIALS AND METHODS

# **Participants**

A student-based sample of 39 (29 female, 10 male) volunteers (mean age = 23.5 years, SD = 6.5) took part in the experiment. All

participants were in standard condition (reported to be healthy) and had normal or corrected-to-normal vision.

# **Apparatus and Stimuli**

The experiment was programmed using PsychoPy (Peirce, 2009). Participants sat about 60 cm in front of the screen. To mimic the characteristic (i.e., self-regulated) features of active continuous information-processing, we used mental arithmetic as one of the primary cultural techniques (Thorndike, 1922; Bills, 1943), practiced among identifiable cultural groups, and amenable to advanced psychometric analysis. In particular, we used a version of the mental-addition and verification task that contained both easy and hard items, using a short response-stimulus interval of 50 ms, which is particularly suitable to examine performance fluctuations (Sanders and Hoogenboom, 1970; Soetens et al., 1985; Steinborn et al., 2010, 2012). In each trial, an addition term together with the result is presented and participants indicated whether the result is either correct or incorrect. They were instructed to verify a correct result by pressing the right key (right index finger) and to falsify an incorrect result by pressing the left key (left index finger). The task contained easy and difficult items differing with respect to the chain length. Items categorized as easy included simple additions (e.g., 4 + 5 = 9; 4 + 5 = 8) while items categorized as difficult included chained additions (e.g., 4 + 5 + 1 + 2 = 12; 4+5+1+2=11). There were 24 easy items and 24 hard items. Each item was presented randomly and equally often (total of 865 trials).

# **Automatic and Controlled Processing Components**

In the present study, we used easy (chain length = 1) and hard (chain length = 4-5) mental-addition items as a proxy for automatic versus controlled processing components in mental arithmetic, which is well-agreed and theoretically backed-up by exemplar-based theories of cognition, learning, and automaticity. This consequently leads to a distinction between two general modes of solving mental-addition problems, a calculation-based mode and one that is based on memory retrieval. In the human-factors domain, this is often referred to as workload (albeit in a more intuitive way) and in most cases, not further specified. For example, Logan (1988) considered performance as automatic when it is based on single-step, direct-access retrieval of solutions from memory, while he considered performance as controlled when it is based on algorithmic processing mechanisms such as counting, addition, memorizing, or borrowing (Groen and Parkman, 1972; Ashcraft, 1992; Imbo et al., 2007). It should be clear that the use of this terminology only makes sense when the context in which the terminology is employed, is also specified (Logan, 1988, pp. 493-495). Crucial is the assumption that every encounter of a stimulus (e.g., 4 + 5 = 9) results in episodic recording and retrieval, given the individual is sufficiently attentive and responsive. More formally, this leads to a set of fundamental assumptions: Attending deliberately to an event such as

a single mental-arithmetic problem furnishes obligatory encoding and obligatory retrieval of separate instances in memory. Stimulus processing is characterized in terms of a race between algorithmic processing and memory retrieval such that whichever finishes first in a particular trial controls the response. In other words, any mental-arithmetic problem in a particular trial is finally solved either by the former or the latter process.

# **Procedure**

For practical reasons, we decided to examine both the effect of texting (Experiment 1) and of phone talking (Experiment 2) on cognition, using the same sample of participants, with these experimental blocks counterbalanced across participants. Each experiment contained a single-task condition (mental arithmetic was performed alone), an expected-load condition (participants anticipated an interruption by an incoming text message or phone call, respectively), and a performed-load condition (mental arithmetic was performed in combination with a memory load or active talking, respectively). Crucially, the text message (Experiment 1) was presented prior to task processing (in order to measure expectancy unconfounded with real task processing), and the expected-load condition (phone call, Experiment 2) occurred shortly after the experimental block. Notably, due to the difficulty to randomize the expected-load condition, we decided to present the three critical experimental conditions in a fixed order (single task, expected load, performed load), which means that differences between the conditions are confounded with potential task order effects. This has important consequences as research hypotheses can only be tested in one direction. That is, we are allowed to ask questions about expected and performed dual-task interference but not about potential benefits (and consequently, the same applies to the interpretation of potential effects). We averaged the single-task condition in order to cushion the impact of all kinds of test-taker effects (i.e., fatigue, practice effects, etc.). Apart from that, one half of the sample was first administered with Experiment 1 (texting: single, expected, and performed) followed by Experiment 2 (phone talking: single, expected, and performed), and the other half of the sample was administered in the counterbalanced order. They were introduced with the experimental paradigm and were instructed to concentrate throughout the experimental session, that is, to respond with maximum speed and accuracy (cf. Ulrich and Miller, 1994).

# Implementation of Phone-Call Expectancy (Experiment 1)

Whether the sole expectation to receive a call from a student colleague affects cognitive performance is an empirical question, and although most people would agree with such a hypothesis from everyday experience, it is difficult to experimentally manipulate aspects of pure expectation such that it mimics the naturalistic aspects of phone calls in real life, regarding relevance and time pressure to answer the impending phone call. Therefore, the nature of this aspect of our study is

exploratory, and only serves to obtain a first impression from the detailed analysis of cognitive processes derived from automatic and controlled processing components of continuous mental addition. The procedure was such that the experimenter informed the participant that he/she will get a phone call during the processing of the task and instructed the participant to answer the call as quickly as possible. The phone lied in front of the participant on the table and called out to him/her to be picked up and used.

# Implementation of Phone Conversation (Experiment 1)

We used the method of story-based natural conversation (cf. Drews et al., 2008), using a scripted semi-structured interview guideline, to mimic the coordinated, joint-activity features of a naturalistic everyday-life small talk conversation among students. The screenplay resembled the method of improvisational theater and contained the following essential elements in the following order (1) become acquainted with each other, telling names, etc. (2) asking about how he/she is doing today, (3) asking about where he/she is living, in which part of the city, etc., (4) asking about what he/she had for lunch, etc., (5) asking about what courses are offered this semester, which courses he/she is currently attending, which his/her favorite lecture and/or professor is, (6) and, for example, what could define a possible motto for the "psychoparty" (an annual party arranged by third-semester students). Further, the interview contained optional elements to ensure the conversation to flow appropriately in the eventual case of the participant being either extremely talkative or taciturn (i.e., to regulate turn-taking). Our aim hereby was to establish a conversation with balanced conversation's proportion, regulating each partner's contribution to the talk toward a value of about 50% (maximal tolerable deviation about 40-60 or 60-40%. These questions were also chosen among a sample of standard questions to retain smalltalk, for example, asking whether he/she like animals, whether he/she is doing sports, whether he/she likes hot wetter, whether he/she knows certain proverbial sayings, etc.

# Implementation of Text Message Expectancy

In a similar way, another exploratory aspect of our study contained the question of whether the sole expectation to receive a text message from a student colleague in some way affects cognition. For example, everyday experience would imply that expecting a text message from a student colleague during a lecture (where the phone is not allowed to be used actively) potentially distracts individuals such that attention is directed away from the content of the lecture toward the potential content of the message. The procedure was such that the experimenter informed the participant that he/she will get text a message during the processing of the task and instructed the participant not to answer the message until the experimental block is finished. Again, the phone lied before the participant on the table and called out to him/her to be picked up and used.

# Implementation of Text Message Communication

The participant obtained a text message and was asked the following questions: "Was ware ein optimales Geburtstagsgeschenk für Dich, wenn der Preis egal ware?" ("What would you want as a birthday present? What would you choose, if money is no object?"). The participant was instructed to think about an answer during the processing of the task and to answer this questions after finishing the experimental block.

# **RESULTS (EXPERIMENT 1: TEXTING)**

## **Data Treatment**

Responses faster than 100 ms were regarded outliers and removed from RT analysis. To effectively take advantage of the full scope of distributional analysis, we only used a minimal-trimming method by removing the three slowest reactions for each of the conditions, according to Ulrich and Miller (1994), and in accordance with our previous use of this method (e.g., Steinborn and Huestegge, 2016). Incorrect responses were regarded response errors and used to compute an index of error rate.

# **Standard Performance Indices**

For each of the experimental conditions, we computed the reaction time mean (RTM) to index average response speed and the RTCV to index relative response-speed variability, according to the suggestion of Flehmig et al. (2007) and Flehmig et al. (2010), and according to our previous use of this method. RTCV is obtained by computing the standard deviation of the RTs (separately for each individual and experimental condition) divided by the individual mean of RTs (for each individual and experimental conditions). Error percentage (EP) indicated the rate of incorrect responses, and served as measure of response accuracy.

# **Distributional Analysis**

To analyze the distribution of responses, we computed the interpolated vincentized CDF of responses with 19 percentiles for each of the experimental conditions according to the suggestion of Ulrich et al. (2007). By means of this analysis, we were to know whether the hypothesized effect of phone conversation is due to a generic slow-down of all responses or alternatively due to a selective slow-down of the long percentiles of the CDF. To more directly account for experimentally induced effects of distributional shape (right-tail density accumulation effects, further referred to as skewness), we additionally adopted an ex-Gaussian model approach but only as a descriptive model of reaction times to analyzing its three parameters mean, dispersion, and shape  $(\mu, \sigma, \text{ and } \tau)$ . We computed ex-Gaussian model parameters for each participant according to the methodical rules provided by Lacouture and Cousineau (2008). Within the context of a chained mental-arithmetic task, parameters  $\mu$ and  $\sigma$  can readily be interpreted as localization and dispersion (around  $\mu$ ) indicators while  $\tau$  is sensitive to experimental effects

TABLE 1 | Mean reaction time (RT) and standard error of the mean (SE) as a function of the factors context and demand, separately for Experiments 1 and 2 (texting vs.

	Factor levels			Experi	ment 1					
	Context	Demand	F	RT (ms)	l	EP (%)		RT (ms)	E	P (%)
			М	SE	М	SE	М	SE	М	SE
1	1	1	993	31.6 (26.6)	1.96	0.23 (0.32)	992	31.55 (47.98)	1.96	0.23 (0.56)
2	1	2	2444	73.6 (31.5)	5.96	0.61 (0.40)	2444	73.58 (36.14)	5.96	0.61 (0.54)
3	2	1	959	28.2 (31.1)	1.19	0.28 (0.26)	941	27.21 (47.72)	2.08	0.43 (0.42)
4	2	2	2431	78.5 (34.7)	5.08	0.68 (0.44)	2324	79.11 (41.54)	5.44	0.68 (0.55)
5	3	1	950	30.7 (29.0)	1.37	0.24 (0.31)	1343	63.04 (47.42)	2.32	0.86 (0.47)
6	3	2	2330	72.2 (31.3)	5.20	0.62 (0.42)	3565	181.48 (134.59)	9.76	1.70 (1.20)

N = 39; RT, reaction time mean; EP, error rate (%); M and SE are population parameters, and SE is transformed for within-subject designs according to Cousineau (2005), shown in brackets.

on right-tail density accumulation (Steinborn and Huestegge, 2016).

# **Standard Analysis**

The design contained the experimental factors context (single task vs. expecting text message vs. handling text message) and demand (easy vs. hard mental arithmetic) and contained RT and error rate as dependent measures. Complete statistical results are referred to in Table 1 and visually displayed in Figure 1. Responses became not slower in the experimental blocks as compared to the single-task condition. As expected, responses were faster in easy than in hard mental-arithmetic trials, as indicated by a main effect of demand on RTM [F(1,38) = 653.7,p < 0.01]. Finally, multitasking did not differentially impose negative effects on automatic and controlled components of mental arithmetic. Finally, it should be mentioned that there was no speed-accuracy trade-off that could compromise the interpretation of effects on RT. In fact, errors were low overall and therefore not further considered (cf. Steinborn et al., 2017).

# **Distributional Analysis**

Besides effects on average response speed, we hypothesized that multitasking increased performance variability in the primary task, which should perhaps be more pronounced for hard than for easy mental arithmetic. However, a visual inspection of the CDFs (Figure 2) indicates that neither expected nor performed text message communication severely affected aspects of distributional skewness in the mental-arithmetic task. There was no significant effect on any parameter of performance variability, with respect to the global GLM effect (Tables 1-3).

# **RESULTS (EXPERIMENT 2: PHONE TALKING)**

# **Standard Analysis**

The design contained the experimental factors context (single task vs. expecting phone call vs. phone talking) and demand (easy vs. hard mental arithmetic) and contained RT and error rate as dependent measures. Complete statistical results

are referred to in Tables 3, 4. Essentially, responses were significantly faster in single-task blocks as compared to the experimental condition, indicating that multitasking affects RTM [F(2,76) = 79.1, p < 0.01]. As expected, responses were faster in easy than in hard mental-arithmetic trials, as indicated by a main effect of demand on RTM [F(1,38) = 422.0, p < 0.01]. More interesting, multitasking differentially affected automatic and controlled components of mental arithmetic, since hard items were more affected than easy items [F(2,76) = 28.6, p < 0.01]. Pre-planned single-comparison analyses revealed that the global GLM effect is driven by the talking-load condition (single task vs. phone talking), indicating a slowing of responses which was differentially more pronounced for hard than for easy arithmetic (Table 3: Panels 7–9). Finally, it should be mentioned that there was no speed-accuracy trade-off that could compromise the interpretation of effects on RT. Errors were in the same direction, thus supporting the conclusion that talking load differentially hampers primary-task processing.

# **Distributional Analysis**

Besides effects on average response speed, multitasking increased the performance variability of the primary task. Notably, a visual inspection of the CDFs (Figure 2) indicates that multitasking affected primary-task performance by destabilizing performance. This is indicated by a main effect of context on the classic variability parameter, RTCV [F(2,76) = 220.9]p < 0.01], which closely corresponds to the visual pattern of skewness of a particular CDF. The main effect of the factor demand on RTCV indicates greater variability for hard than for easy items [F(1,38) = 23.7, p < 0.01], and the context × demand interaction on RTCV indicates that multitasking evoked performance variability to a larger degree in the controlled than in the automatic component of mental arithmetic [F(2,76) = 6.1, p < 0.01]. Since recommended by several authors (Heathcote et al., 1991; Steinhauser and Huebner, 2009), we additionally obtained parameter of skewness from an ex-Gaussian distributional model. As expected, the destabilizing effect on performance is also (even more sensitively) indicated by a main effect of the factor context on the ex-Gaussian  $\tau$  parameter [F(2,76) = 97.0, p < 0.01], and by

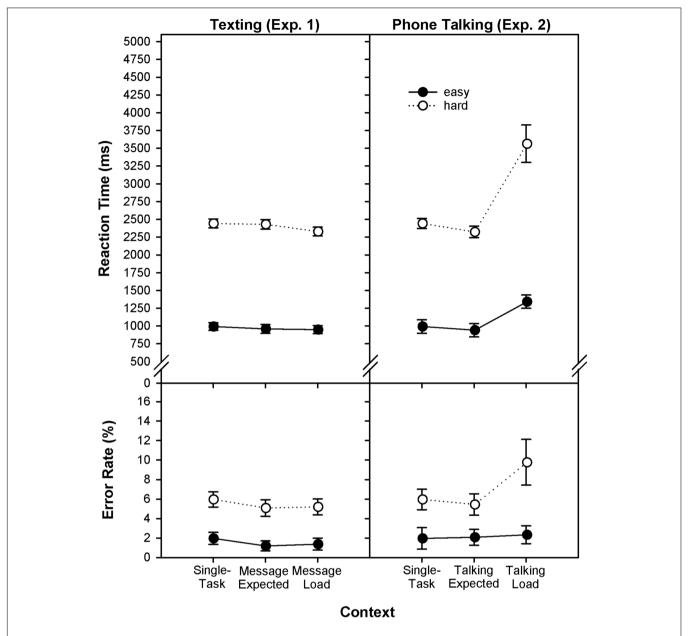


FIGURE 1 | Reaction time mean and error rate (RTM, EP) as a function of the factors context (single-task vs. expected load vs. load) and demand (easy vs. hard) in continuous mental arithmetic, separately displayed for Experiments 1 (texting) and 2 (phone talking).

the context  $\times$  demand interaction effect on the  $\tau$  parameter  $[F(2,76)=36.0,\ p<0.01]$ . Pre-planned single-comparison analyses revealed that the global GLM effect is driven by the talking-load condition (single task vs. phone talking), indicating a slowing of responses which was differentially more pronounced for hard than for easy arithmetic (**Tables 4, 5**: Panels 7–9). Thus, results indicate that phone talking during continuous primary-task performance affects not simply the speed of information-processing throughput (Humphreys and Revelle, 1984; Thorne, 2006; Steinborn et al., 2010), but crucially, the reliability of these processes, supporting an attentional-failure hypothesis rather than a general slow-down

hypothesis of smartphone-conversation effects on cognitive work.

# **DISCUSSION**

# **Summary**

The aim of this applied study was to examine the effects of (secondary-task) smartphone communication on (primary-task) performance in chained mental arithmetic. The results can be summarized as follows: (1) Contrary to popular opinion, neither the sole expectation of an impending text

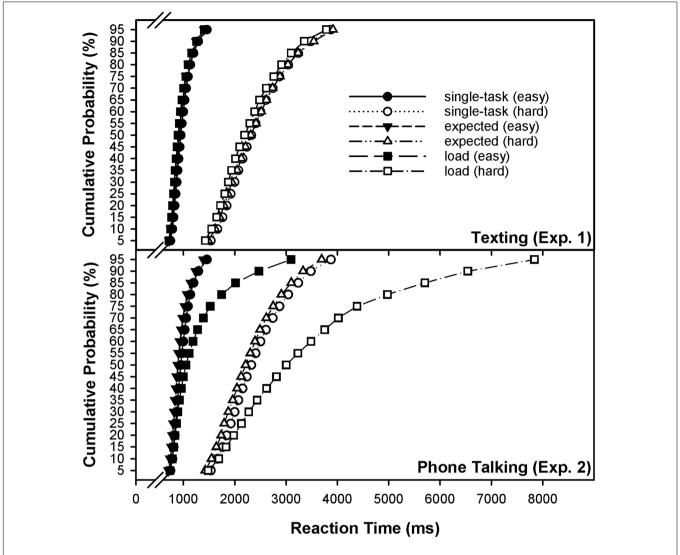


FIGURE 2 | Vincentized and interpolated cumulative distributive function (CDF) of reaction times for each combination of the factors context (single-task vs. expected load vs. load) and demand (easy vs. hard) in continuous mental arithmetic, separately displayed for Experiments 1 (texting) and 2 (phone talking).

message (a question) nor the mental preoccupation with finding an answer (to the question delivered by the text message) had any detrimental effect on primary-task performance. (2) Further, the expectation of an impending phone call was also not detrimental to primary-task performance. (3) However, active conversation was clearly detrimental to primary-task performance, since responses were slower on average in the talking-load condition as compared to the single-task condition. (4) Importantly, talking did not yield a constant slowing but rather a destabilization of continuous mentalarithmetic performance, since the CDF analysis revealed increased distributional skewness beyond scaling variability. (5) The destabilization effect was more pronounced for hard than for easy items, indicating a differential effect on controlled versus automatic components of mental arithmetic. This result might be important to our understanding of how smartphone communication affects cognitive functioning in

general, and might also be of applied importance because it may help to understand better how phone conversation impacts on a driver's ability to allocate attention to the task of driving.

# Effects of Expected Multimedia-Based Communication

Most people would agree, when asked, that impending but temporally uncertain social interaction at the workplace or elsewhere is distracting and can sometimes be even annoying. Further, researchers and practitioners in applied fields would also agree that multimedia-based communication devices represent the biggest distraction at work, despite the methodical difficulties to develop a model (i.e., a micro-case) that exactly mimics the interactive features of multimedia-based communication in natural environments (Ralph et al., 2014, 2015). Therefore, the results presented here are of explorative character, although they

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TABLE 2 | Results of the experimental effects on standard performance indices (Experiment 1).

	Source: Overall		RTM			EP			RTCV		
		df	F	р	η <sup>2</sup>	F	р	η²	F	р	η2
1	Context	2,76	11.1	0.000	0.23	3.5	0.039	0.08	2.9	0.073	0.07
2	Demand	1,38	653.7	0.000	0.95	61.6	0.000	0.62	112.0	0.000	0.75
3	Context × Demand	2,76	6.0	0.004	0.14	0.0	0.960	0.00	1.1	0.326	0.03
	Source: Single vs. Expected										
4	Context	1,38	1.6	0.211	0.04	8.2	0.007	0.18	1.8	0.186	0.05
5	Demand	1,38	653.7	0.000	0.95	61.6	0.000	0.62	112.0	0.000	0.75
6	Context × Demand	1,38	0.5	0.474	0.01	0.0	0.856	0.00	1.0	0.319	0.03
	Source: Single vs. Load										
7	Context	1,38	17.6	0.000	0.32	3.9	0.055	0.09	5.4	0.026	0.12
8	Demand	1,38	653.7	0.000	0.95	61.6	0.000	0.62	112.0	0.000	0.75
9	Context × Demand	1,38	6.4	0.015	0.15	0.1	0.801	0.00	2.2	0.144	0.06

Effect size:  $\eta_p^2$ ; Experimental factors: Context (single-task vs. text message expected vs. text message load), Demand (easy vs. hard mental arithmetic); RTM, reaction time mean; EP, error percentage (%); RTCV, reaction time coefficient of variation.

TABLE 3 | Results of the experimental effects on ex-Gaussian parameters (Experiment 1).

	Source: Overall			μ (Mean)	an) σ (Variability)		$\tau$ (Skewness)				
		df	F	р	η <sup>2</sup>	F	р	η2	F	р	η²
1	Context	2,76	18.8	0.000	0.33	2.9	0.074	0.07	2.6	0.085	0.06
2	Demand	1,38	331.0	0.000	0.90	97.3	0.000	0.72	164.0	0.000	0.82
3	Context × Demand	2,76	7.9	0.001	0.17	1.6	0.220	0.04	2.7	0.074	0.07
	Source: Single vs. Expected										
4	Context	1,38	5.1	0.030	0.12	0.3	0.566	0.01	2.1	0.159	0.05
5	Demand	1,38	331.0	0.000	0.90	97.3	0.000	0.72	164.0	0.000	0.82
6	Context × Demand	1,38	1.8	0.118	0.05	0.4	0.523	0.01	3.3	0.077	0.08
	Source: Single vs. Load										
7	Context	1,38	49.1	0.000	0.56	9.7	0.003	0.20	5.9	0.020	0.14
8	Demand	1,38	331.0	0.000	0.90	97.3	0.000	0.72	164.0	0.000	0.82
9	Context × Demand	1,38	20.4	0.000	0.35	4.9	0.032	0.12	6.0	0.019	0.14

Effect size:  $\eta_c^2$ ; Experimental factors: Context (single-task vs. text message expected vs. text message load), Demand (easy vs. hard mental arithmetic).

TABLE 4 | Results of the experimental effects on standard performance indices (Experiment 2).

	Source: Overall			RTM			EP			RTCV	
		df	F	р	η <sup>2</sup>	F	р	η <sup>2</sup>	F	р	η²
1	Context	2,76	79.1	0.000	0.68	4.0	0.047	0.10	220.9	0.000	0.85
2	Demand	1,38	422.0	0.000	0.92	62.4	0.000	0.62	23.7	0.000	0.47
3	Context × Demand	2,76	28.6	0.000	0.43	8.9	0.001	0.19	6.1	0.003	0.14
	Source: Single vs. Expected										
4	Context	1,38	10.3	0.003	0.21	0.3	0.583	0.01	2.9	0.097	0.07
5	Demand	1,38	422.0	0.000	0.92	62.4	0.000	0.62	23.7	0.000	0.47
6	Context × Demand	1,38	3.7	0.063	0.09	0.7	0.402	0.02	0.0	0.882	0.00
	Source: Single vs. Load										
7	Context	1,38	70.3	0.000	0.65	3.4	0.073	0.08	247.0	0.000	0.87
8	Demand	1,38	422.0	0.000	0.92	62.4	0.000	0.62	23.7	0.000	0.47
9	Context × Demand	1,38	26.2	0.000	0.41	10.8	0.002	0.22	7.9	0.008	0.17

Effect size:  $\eta_p^2$ ; Experimental factors: Context (single-task vs. text message expected vs. text message load), Demand (easy vs. hard mental arithmetic); RTM, reaction time mean; EP, error percentage (%); RTCV, reaction time coefficient of variation.

might reveal aspects that are relevant for the practical use in future studies. Contrary to our expectations, and to popular beliefs based on everyday experience, expecting an impending text message (containing a question) in our study did not hamper performance in the primary task (Experiment 1). Further, the load imposed with finding an answer (to the question delivered by the text message) did also not detrimentally affect any aspect of primary-task performance (Figures 1, 2). However, it would be premature to conclude that impending text messages are unproblematic with regard to possible distraction effects on primary-task performance, since one cannot definitely exclude that more demanding text messages might affect performance in the primary task.

In Experiment 2, we asked whether the expectation to receive a call from a student colleague affects cognitive performance in the primary task. Likewise as in Experiment 1, expecting an impending phone call was not at all detrimental to primary-task performance. In contrast, actively performed conversation (talking) was clearly detrimental to primary-task performance, since responses were slower on average in the talking-load condition as compared to the single-task condition. Thus, these data would indicate the conclusion that impending phone-call expectancy is not harmful to the individual currently engaged in deliberate information-processing activity, which is counterintuitive to what one would expect from everyday experience. Such findings are often interpreted such that the anticipation of impending distraction could have evocated additional capacity (or enforced a strategy of cognitive shielding) and by this means prevented any impairment of primary-task performance to occur (Fuentes and Campoy, 2008; Bratzke et al., 2009, 2012; Langner et al., 2010, 2011; Szalma and Hancock, 2011; Scheiter et al., 2014). Due to the chosen design features of our study, however, hypotheses could only be formulated in one direction (i.e., toward potential dual-task interference costs, not benefits), and results will thus only be interpreted accordingly. Instead, some critical issues are outlined below.

Critical to a manipulation of expected-load effects (Experiment 1) are two aspects, (1) the nature and degree of demand related to processing a text message, (2) and the experimental means of performing controls to determine secondary-task engagement (i.e., to determine how long and how intensely the participants were processing the text message). Critical to a manipulation of expectancy for an impending phone call (Experiment 2) are two further aspects, (3) the experimental methods of inducing an internal state of hurry (i.e., the problem of getting the participants to act with the required urgency), (4) and the methods of controlling for when exactly and how often the participants re-started to preparing for the anticipated event. Within a spare-utilized capacity threading model and related accounts, these intrusions are reflected in aspects of intraindividual performance variability. For example, McDaniel et al. (2004) considered several aspects relevant to study performance costs related to a monitored event. As a general rule, it is important to ascertain whether the phone call can easily be detected perceptually (e.g., phone nearby in sight vs. far-apart, ringing loud vs. muted, etc.), whether the occurrence uncertainty is event-based or time-based (e.g., phone

call expected after lunch, or at around 12.00 am), and whether there is time pressure to answer the call pointing on a distinction between immediate-execute vs. delayed-execute secondary-task mode (McDaniel and Einstein, 2000; McDaniel et al., 2004; Einstein and McDaniel, 2005).

# **Effects of Phone Conversation (Talking)**

Researchers usually agree with the allegation that active conversation requires attention for monitoring semantic aspects such as topic and content, for coordinating the time-critical aspect of turn taking (between speaking and listening), and for a rather metacognitive supervision of conversational balance (Kahneman, 1973, pp. 5-12; Salvucci and Taatgen, 2011, pp. 3-24). This means that conversation is a complex matter affected by many factors and therefore difficult to examine in a wholistic fashion (Drews et al., 2008; Bergen et al., 2013). Notably, the problem is actually recognized and is a current point of contention among researchers in basic-research and applied-research domains (cf. Drews et al., 2008, pp. 393-395). In the present study, we decided to examine the effect of phone conversation on cognition by means of the classic continuous dual-task paradigm, where a primary task is performed in streams of continuous action, and where a secondary task is used as a loading or distractor condition, or to "probe" mental focus during primary-task processing (Posner and Boies, 1971, pp. 401-407). Our results indicate that active phone conversation had an enormous impact on mental-arithmetic performance, since the load imposed by conversation yielded slower and somewhat more erroneous responses, as compared to a standard (single-task) condition (Figure 1).

Importantly, phone talking not solely slowed but rather destabilized primary-task performance, as indicated by measures of response-speed variability, which was again more pronounced for hard than for easy mental arithmetic (Tables 4, 5). Thus, the decrements on RT mean are not interpretable by itself (cf. Miller, 2006, p. 93), since it could be demonstrated that they actually originate from a selective slow-down of responses at long CDF percentiles. It becomes evident from Figure 2 that the experimental conditions (standard vs. talking load) are not very different at the shorter percentiles of the CDF while the difference increases substantially toward the longest percentiles. Figure 3 displays a delta plot of the loading effect on mental-arithmetic performance, comparably for the low-demand and the highdemand condition. A delta plot is obtained by calculating the RT difference as induced by an experimental manipulation (e.g., single-task vs. load) against the mean of both experimental conditions for each of the percentiles. By this means, effects of concurrent phone conversation can be evaluated relative to the mean of level of performance, indicating that individuals were not particularly going slower overall but especially became less persistent. In this way, delta plots provide a convenient simplification of the relatively complex information present in the CDFs (cf. De Jong et al., 1994; Ridderinkhof, 2002; Schwarz and Miller, 2012; Ulrich et al., 2015; Steinborn et al., 2016b).

Therefore, the main conclusion our study provides is that phone conversation during mental arithmetic does not globally hamper information-processing speed. Rather, the data indicate

**TABLE 5** | Results of the experimental effects on ex-Gaussian parameters (Experiment 2).

	Source: Overall			μ <b>(Mean)</b>		σ (Variability)			$\tau$ (Skewness)		
		df	F	р	η <sup>2</sup>	F	р	η <sup>2</sup>	F	р	η <sup>2</sup>
1	Context	2,76	7.9	0.002	0.17	2.0	0.150	0.07	97.0	0.000	0.72
2	Demand	1,38	434.0	0.000	0.92	98.3	0.000	0.72	138.6	0.000	0.77
3	Context × Demand	2,76	3.3	0.040	0.08	0.6	0.527	0.04	36.0	0.000	0.49
	Source: Single vs. Expected										
4	Context	1,38	9.1	0.005	0.19	0.8	0.353	0.02	0.1	0.706	0.00
5	Demand	1,38	434.0	0.000	0.92	98.3	0.000	0.72	138.6	0.000	0.77
6	Context × Demand	1,38	3.1	0.087	0.08	0.5	0.484	0.01	0.3	0.576	0.01
	Source: Single vs. Load										
7	Context	1,38	14.0	0.001	0.27	3.9	0.054	0.09	107.4	0.000	0.74
8	Demand	1,38	434.0	0.000	0.92	98.3	0.000	0.72	138.6	0.000	0.77
9	Context × Demand	1,38	6.7	0.014	0.15	1.2	0.290	0.03	43.7	0.000	0.54

Effect size: η<sup>2</sup><sub>n</sub>; Experimental factors: Context (single-task vs. text message expected vs. text message load), Demand (easy vs. hard mental arithmetic).

that load of this kind makes individuals less reliable and less capable to protecting the cognitive system against attention failure. The probability of committing such failures of attention depends on the processing demand of the primary task, being lower for easy than for hard mental arithmetic. This indicates that secondary-task conversation differentially affects automatic and controlled information processing in the primary task. In this way, our study might contribute some important aspects to the understanding of phone-conversation effects on everyday-life tasks such as driving, despite the fact that we employed a continuous mental-arithmetic task to study conversation-related attentional impairments. Thus, particular key characteristics of our study might be those of creating connections between basic and applied research along the concept of a two-state model of attentional failures. For example, Briem and Hedman (1995) concluded that simple phone conversation is in itself not sufficient to adversely affect the ability to maintain road position, but rather increases the risk of traffic accidents by an unfortunate coincidence of a critical traffic event and spontaneous attention failure within the individual (cf. Reason, 1990; Folkard, 1997).

# Theory and Design Issues

Our theorizing is primarily based upon an intermittent spare-utilized capacity threading model as a general framework, in order to account for two essential findings. The first relates to the empirical fact that loading effects by phone conversation on primary-task performance can primarily be located at a cognitive (not at a peripheral-activity) level. The second refers to the possibility, implied by previous findings, that phonerelated interference does impose a constant amount of costs (of sharing capacity) on primary-task performance, but temporarily blocks information processing in the primary task (by a processing bottleneck) in an all-or-none fashion. In this way, our study diverges from the majority of applied multitasking research where the theorizing usually occurs within the multipleresource model framework. For example, Wickens (1984) originally assumed that successful multitasking depends on the compatibility of input systems, representational format, and output systems. From this account, one would have to argue that

(auditory-verbal-vocal) phone conversation may be performed concurrently with little or no costs to a (visual-spatial-manual) task as continuous mental arithmetic. Given the apparent three-dimensional compatibility of this dual-task combination, phone conversation and continuous mental arithmetic should be performed together with no interference, which was obviously not the case in our study (cf. Strayer and Drews, 2007).

The basic tenet of a spare-utilized capacity threading (monitoring-focus) model is that there is an intermittent exchange between capacity for task operations and for monitoring. Crucial is the notion of intermittency, as task processing is interrupted during monitoring, which means that as individuals engage in active task operations, spare capacity is conveyed to utilized capacity. Thus, a temporary increase in task focus would yield a corresponding (temporary) decrease in monitoring. A spare-utilized capacity threading model is not only consistent but even relies on the notion of a processing bottleneck, as it assumes that individuals can (effectively) engage in only one of the two, task processing or monitoring. In this way, it is mutually exclusive with the notion of (temporarily–punctual) sharing of capacity. This means that the relation of utilized versus spare capacity is constantly fluctuating across subsequent trials as this relation is continually evaluated and re-adjusted, which means that capacity for active task operations varies across trials. Remind that several empirical findings of Strayer et al. (2003) support this position, suggesting that even when talking drivers direct their gaze at objects in the environment, they often fail to see them. To put it more precisely, there is an increased probability for drivers currently engaged in active conversation to commit attention failure (in a temporarily punctual fashion) to recognize objects in the environment.

A theoretical alternative to the prevalent multiple-resource framework in applied-multitasking research (Wickens, 1980, 1984), therefore, is that conversation-related interference stems from an intermittent postponement imposed by a discrete-processing bottleneck such that attending to the phone conversation temporarily blocks information processing in the primary task, because the bottleneck forces serial processing between talking and performing continuous arithmetic. Such

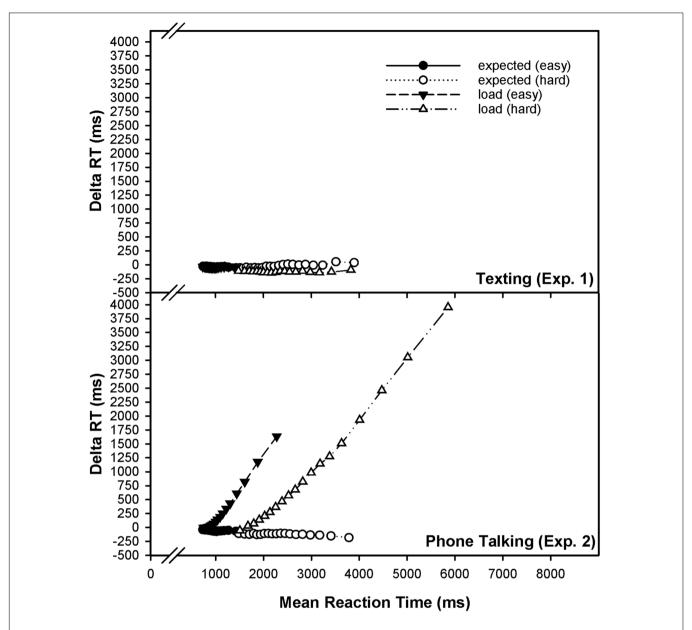


FIGURE 3 | Delta plots of the distraction effect by cell-phone usage. For each percentile, the RT difference between the experimental conditions (single-task vs. expected load; single-task vs. load) is plotted against the mean of the conditions in that percentile. Data are separately displayed for Experiments 1 (texting) and 2 (phone talking).

a view of trial-by-trial intermittent resource allocation offers a completely natural way to explain variability that is usually observed in RT experiments. In (low-error domain) RT tasks, these trial-by-trial fluctuations in the rate of utilized capacity (task focus) are reflected in the right tail (skewness) of the intraindividual RT distribution. The results of the present study are completely in line with such a perspective: As visually displayed in Figures 2, 3, individuals were partially capable to retain a high level of primary-task performance during talking (as compared to the standard condition), which is particularly true for automatic (vs. controlled) processing, but are partially prone to commit a failure to engage in processing the primary

task. That is, they are not very different at the shortest percentiles of the CDF while the difference increases substantially toward the longest percentiles, and this effect differentially depends on the demand imposed by the primary task. According to Strayer and Drews (2007), conversation is special in that thought packages cannot be broken into arbitrary units but instead is composed of turns that engage the central-processing bottleneck.

# **Final Conclusion**

A final word ought be devoted to the fundamental question of how an applied multitasking study should be conducted in order to satisfy the requirements of ensuring experimental

control (i.e., internal validity), on the one hand, and to provide representativeness of the created micro case (i.e., external validity), on the other hand. Although the problem has been recognized by theoreticians of outstanding reputation (e.g., Pashler, 1998, pp. 5-31; Sanders, 1998, pp. 452-506; Salvucci and Taatgen, 2011, pp. 237-253), no definite solution has been offered probably because the problem is unsolvable as it is a problem of perspective. An essential characteristic of applied research relates to the complexity of the real-life situation and the variety of possible influences and effect mechanisms. The dilemma is that isolating the separate influence of the independent variables increases internal validity but decreases representativeness. For example, Drews et al. (2008) criticized the frequently observed practice of reducing complexity to increase experimental control to study conversation-related interference, arguing that many tasks employed to simulate conversation in studies on cell phone use on driving suffer from serious ecological-validity concerns. For example, several studies used "verbal tasks" as representative for conversation, administering participants to decide between words and non-words, or to perform verbal-reasoning tasks as secondary-task assumed to interfering with primary-task performance. In any case, artificial tasks fail to mimic the features of real conversation.

We used the method of story-based natural conversation, using a scripted interview guideline, to simulate the selfregulated dyadic-activity characteristics of naturalistic everyday small talk conversation among students. The interview was semi-structured but contained optional elements to ensure the conversation to flow appropriately. We intended to establish a talking-load condition with balanced conversation's proportion, being aware that varying the proportion between listening and speaking might be a potential source of interference measurable in continuous dual-task situations. For example, McCarley et al. (2004) found impairments in the ability of participants to detect changes in real-world traffic scenes when they were conversing on a handsfree device, however, no such performance decrements were observed when participants listened to prerecorded conversations from other participants. These findings are important since they demonstrate that listening to verbal material is by itself not sufficient to produce the dual-task interference associated with using a cell phone while driving. In any case, a more in-depth analysis of the particular components of real-life conversation is vital for the complete understanding of conversation-related interference in future studies. For the time being, we conclude that phonerelated interference effects on cognition does not arise from a constant slow down but from an occasional break down of mental efficiency during continuous mental arithmetic performance.

The key contribution of our study embraces two aspects, knowledge related to the particular component processes affected by conversation in continuous dual-task situations, methodology of design and experimental set-up (Steinborn et al., 2017), and advanced measurement technology (Steinborn et al., 2016b). First, our results provide knowledge to the community since we determined component processes related to automatic and controlled information processing as they were affected by concurrent phone conversation. Second, we provide a methodical advancement to study conversationrelated interference on primary-task performance within the framework of mental chronometry. In the focus of our research project stands the goal of measuring the effects of phone talking on automatic and controlled information processing with high precision, by analyzing the entire RT distribution instead of only analyzing RT means. The main conclusion our study provides is that interference by phone conversation is not due to a constant slowdown but rather due to an occasional breakdown of continuous information processing, which differentially affects automatic and controlled components of information processing. In effect, we argue that phone conversation makes individuals vulnerable to attention failure (being greater for controlled vs. automatic components), and in this way, hampers stability of information-processing throughput (Humphreys and Revelle, 1984; Steinborn et al., 2016b).

# **ETHICS STATEMENT**

Written informed consent was obtained from the participants regarding their agreement with their participation in this research. Our study was in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

#### **AUTHOR CONTRIBUTIONS**

Ideas and theorizing: MS and LH. Experiment and data analysis: MS. Interpreting results: MS and LH. Writing of the manuscript: MS.

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# **High-Frequency Binaural Beats Increase Cognitive Flexibility: Evidence from Dual-Task Crosstalk**

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Increasing evidence suggests that cognitive-control processes can be configured to optimize either persistence of information processing (by amplifying competition between decision-making alternatives and top-down biasing of this competition) or flexibility (by dampening competition and biasing). We investigated whether highfrequency binaural beats, an auditory illusion suspected to act as a cognitive enhancer, have an impact on cognitive-control configuration. We hypothesized that binaural beats in the gamma range bias the cognitive-control style toward flexibility, which in turn should increase the crosstalk between tasks in a dual-task paradigm. We replicated earlier findings that the reaction time in the first-performed task is sensitive to the compatibility between the responses in the first and the second task-an indication of crosstalk. As predicted, exposing participants to binaural beats in the gamma range increased this effect as compared to a control condition in which participants were exposed to a continuous tone of 340 Hz. These findings provide converging evidence that the cognitive-control style can be systematically biased by inducing particular internal states; that high-frequency binaural beats bias the control style toward more flexibility; and that different styles are implemented by changing the strength of local competition and top-down bias.

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#### INTRODUCTION

The concept of cognitive control refers to processes that are not directly involved in processing and selecting stimulus events or actions but that rather orchestrate the processes responsible for these basic functions. Control processes are commonly characterized in terms of their capacity limitations but there is increasing evidence that they can also vary in style. Both functional (Goschke, 2003; Dreisbach and Goschke, 2004) and neural (Cools, 2008, 2012; Cools and D'Esposito, 2011) considerations suggest that cognitive-control states can vary both intra- and inter-individually to the degree that they either focus the available processing capacity on one single event or task or distribute capacity more widely across various processes or tasks. Following these leads, Hommel (2015) has suggested that the style of control varies between persistence and flexibility: while the former implies highly focused, exclusive processing, the latter implies a broad distribution of resources and rather integrative processing. As the current settings on the persistence-flexibility dimension affect both the basic cognitive operations and the operation characteristics of the superordinate cognitive-control processes, Hommel (2015) refers to the process of adjusting and changing the settings as "metacontrol" and to the resulting settings or states as "metacontrol states."

There are increasing attempts to identify means to bias metacontrol states in systematic ways, which is of both theoretical and practical relevance. It is of theoretical relevance because the characterization of effective means to bias the metacontrol state or control style provides constrains for understanding its underlying functional and neural mechanisms. And it is of practical relevance because effective means point to interesting methods for individually tailored cognitive enhancement, which for instance might seek to support individuals to implement particularly adaptive states according to their needs. The present study assessed an enhancement technique that has been frequently claimed to target cognitive control functions: binaural beats—the subjective experience of a beating tone with a frequency that corresponds to the frequency difference between two binaurally presented tones (Oster, 1973). Originally, binaural beats of low frequency have been argued to induce mental relaxation while high frequencies were assumed to induce alertness and attentional concentration (Vernon, 2009; Turow and Lane, 2011). This would suggest that high-frequency beats bias cognitive control toward persistence and focus, but recent findings suggest the exact opposite.

In a recent study, we presented participants with highfrequency binaural beats (gamma range), low-frequency binaural beats (alpha range), or a continuous tone of 340 Hz (Reedijk et al., 2015) before they performed an attentional blink task (Raymond et al., 1992). In this task, participants are presented with two visual targets in a rapid stream of stimuli, which commonly leads to the observation that they often miss the second target if it is presented briefly after the first. The impact of the low-frequency beats on the attentional blink did not differ from the control condition, while the high-frequency beats reduced the attentional blink significantly in individuals with low striatal dopamine. The presence of the attentional blink has been attributed to over-control (Olivers and Nieuwenhuis, 2006)i.e., a too strong focus on the first target, which leaves too few resources for the second. This suggests that high-frequency beats lead to a broader distribution, rather than to a stronger focus, of available resources—to more cognitive flexibility that is. This interpretation would fit the observation that binaural beats in the gamma range can improve performance in a divergent thinking task, but not in a convergent thinking task (Reedijk et al., 2013), as divergent thinking should benefit more from broadly distributed resources than convergent thinking.

The present study sought for converging evidence for the idea that binaural beats in the gamma range might bias cognitive control toward flexibility. In previous studies, control biases toward persistence or flexibility have been assessed by means of crosstalk between different event representations or across multiple tasks (e.g., Dreisbach and Goschke, 2004). Of particular relevance for our present study, Fischer and Hommel (2012) have tested participants in a dual-task paradigm after having primed them with a convergent-thinking task or a divergentthinking task. The dual-task paradigm was chosen to produce the well-established psychological refractory period (PRP) effect (see Pashler, 1998, for an overview): the observation that a response (R2) to a stimulus (S2) is slower the sooner this stimulus appears after the presentation of another stimulus (S1) signaling another response (R1). In other words, the reaction time for the second of two responses (RT2) increases as the interval between S1 and S2 (the stimulus onset asynchrony or SOA) decreases. The idea was that a convergent or divergent priming task would bias the control style toward persistence versus flexibility, respectively. The dependent measure of interest was the degree of crosstalk from the second on the first task. As previously demonstrated, RT1 (the reaction time in the first-performed task) is sensitive to the compatibility between the response in the first task (R1) and the response in the second (R2: Hommel, 1998; Logan and Schulkind, 2000); for instance, the time it takes to press the left of two keys in the first task (R1) is faster if the second task also requires a left keypress (R2). This demonstrates that R2 is activated before R1 selection is completed, which makes the response-compatibility effect (RCE) an indicator of the degree of distributed, parallel processing (Logan and Gordon, 2001; Lien and Proctor, 2002).

As one would expect from this reasoning, Fischer and Hommel (2012) found a smaller RCE if participants were primed with a convergent-thinking rather than a divergent-thinking task. If we assume that engaging in divergent thinking leads to a more broadly distributed allocation of processing resources, and that this bias toward more flexibility was sufficiently inert to affect performance in the overlapping dual task, we can conclude that the size of the RCE reflects the relative bias toward persistence and flexibility. If our hypothesis that high-frequency binaural beats bias the cognitive control style toward flexibility is correct, presenting participants with high-frequency beats should thus increase their RCE in a dual task that manipulates R1-R2 compatibility. We tested this prediction by adopting a task comparable to that used by Fischer and Hommel (2012) and having participants perform it after presenting them with either high-frequency binaural beats (the gamma group) or with a continuous tone of 340 Hz (the control group). Given that binaural beats may impact mood (Chaieb et al., 2015), heart rate, and human blood pressure (Carter, 2008), we also assessed participants' subjective affective states, heart rate, and blood pressure before and after the dual-task performance.

# MATERIALS AND METHODS

# **Participants**

Forty students (32 female, eight male; aged 18-27 years old) from Leiden University took part in exchange for course credit or pay. All had normal or corrected-to-normal sight and hearing. Participants were selected individually using the Mini International Neuropsychiatric Interview (M.I.N.I.; Sheehan et al., 1998), a well-established brief diagnostic tool in clinical, drug and stress research that screens for several psychiatric disorders and drug use (Sheehan et al., 1998; Colzato and Hommel, 2008; Colzato et al., 2008). A group of randomly selected 20 participants (15 female, five male) was exposed to gamma-frequency (40 Hz) binaural beats and the other 20 (17 female, three male) were assigned to a control condition, in which they were exposed to a constant tone of 340 Hz.

#### **Ethical Statement**

Written informed consent was obtained from all subjects; the protocol and the remuneration arrangements of 5 euro were approved by the local ethical committee (Leiden University, Institute for Psychological Research).

# **Dual-Task Paradigm**

Like Fischer and Hommel (2012), we adopted the dual-task paradigm from Fischer et al. (2007; see also Logan and Schulkind, 2000), in which both tasks required participants to categorize the stimuli as being smaller vs. larger than 5. To avoid identical stimuli in both tasks (e.g., perceptual match) and to maintain the numerical distance to 5, the digits 3 and 7 and digits 2, 4, 6, and 8, presented in white on black background, served as stimuli for Task 1 (S1) and Task 2 (S2), respectively (Fischer et al., 2007). The same categorization of S1 and S2 (i.e., either both smaller or both larger than 5) implied a match between R1 and R2 categories, that is, response-category compatibility or response compatibility for short. Accordingly, opposite categorizations (i.e., S1 smaller and S2 larger than 5 or vice versa) implied response incompatible ty, so that performance differences between response-compatible and response-incompatible trials reflect the RCE.

Participants were to press one of two keys in each task: the "," and "." key of the QWERTZ keyboard to S1, by using their right index and middle finger, and the "Y" and the "X" key to S2, by using their left middle and index finger. The stimulus-response mappings were counterbalanced across participants. Each trial began with a 500-ms fixation display, next to which S1 appeared above the screen center. Following an SOA of 40, 130, 300, or 900 ms, S2 appeared below screen center for 1000 ms. Both stimuli were replaced by a 2-s blank screen, followed by the 300 ms feedback "correct" or, in case of an incorrect response in either task, a missing response, or incorrect response order, the feedback "error." Participants were asked not to group responses and to respond as fast and as accurately as possible, first to S1 and only second to S2 (Task 1 priority). Participants performed 64 practice trials, followed by three experimental blocks of 64 trials each.

#### **Procedure**

Participants were tested individually. Upon arrival, they were asked to rate their mood on a 9 × 9 Pleasure × Arousal grid (Russell et al., 1989), with values ranging from -4 to 4. The resulting score thus indicated the location of the participant's affective state within a two-dimensional space defined by hedonic tone and activation. Subsequently, participants listened to gamma-frequency (40 Hz) binaural beats or a constant tone of 340 Hz (control condition), all embedded in white noise to enhance clarity of the beats (Oster, 1973), for 3 min before and during the dual-task paradigm (training and experimental blocks). Binaural beats were presented through inear headphones (Etymotic Research ER-4B microPro), which provide 35 dB noise attenuation. The binaural beats were based

on a 340 Hz carrier tone, which was used as the constant tone in the control condition. After the dual-task paradigm, participants rated their mood for the second time. After these measurements the experimental session ended and participants were paid, debriefed, and dismissed.

# **Statistical Analyses**

In view of the relatively small number of trials in each design cell we did not trim the data but analyzed median rather than mean RTs to reduce the impact of outliers. To assess whether binaural beats modulate dual-task performance, median RTs data for T1 and T2 were submitted to two separate repeated-measures analyses of variance (ANOVAs) with SOA (40 vs. 130 vs. 300 vs. 900) and Response Compatibility (R1-R2 compatible vs. R1-R2 incompatible) as within-participants factors and group (control vs. gamma) as between-participants factor.

Incorrect T1 (M=1.4%, SEM=0.2) and T2 responses (M=4.2%, SEM=0.6) were excluded and the analyses were restricted to trials in which both responses were correct. Mood (pleasure and arousal scores), heart rate (HR), systolic blood pressure (SBP) and dystolic blood pressure (DBP) were analyzed separately by means of repeated-measures ANOVAs. Effect of time (first vs. second measurement) served as within-subjects factor and group (gamma vs. control) as between-subject factor. A significance level of p<0.05 was adopted for all statistical tests. In case of significant interaction, post hoc analyses were conducted using Tukey HSD test.

### **RESULTS**

#### **Participants**

No significant group differences were observed in terms of age (M=19.8, SEM=0.6 and M=20.25, SEM=0.7 for the control and gamma group, respectively), t(38) < 1, p=0.64, or gender distribution (F/M = 17/3 and 15/5 for the control and gamma group, respectively),  $\chi 2 < 1$ , p=0.43.

#### RT1

The main effect of SOA was significant, F(3,114) = 10.524, p < 0.001,  $\eta_p^2 = 0.22$ , indicating faster RTs with increasing SOA. *Post hoc* analyses showed that RTs were significantly slower at SOA-40 and SOA-130 than at SOA-300 and SOA-900 ( $p_s \le 0.007$ ). No significant differences were observed between SOA-40 and SOA-130 (p = 0.999), or between SOA-300 and SOA-900 (p = 0.62).

The main effect of Response Compatibility was also significant,  $F(1,38)=15.799,\ p<0.001,\ \eta_p^2=0.29,\$ with participants being faster in categorizing S1 when S1 and S2 belonged to the same response category (M=566, SEM=12.7) than when they did not (M=591, SEM=17.7) (see **Figure 1** and **Table 1**). This effect was significant for short SOAs only (68 and 43 ms for SOA-40 and SOA-130, respectively,  $p_s<0.001$ ), but not for long SOAs (12 and 0 ms, for SOA-300 and SOA-900, respectively,  $p_s\ge0.88$ ), as revealed by a significant interaction between SOA and Response Compatibility,  $F(3,114)=17.78,\ p<0.001,\ \eta_p^2=0.32$ . More importantly,

we observed a significant interaction between group and Response Compatibility, F(1,38) = 4.33, p = 0.04,  $\eta_p^2 = 0.10$ , showing that the compatibility effect was significantly (and more than three times) larger in the gamma group (38 ms) than in the control group (12 ms). No other significant effects were found,  $F_{\rm s} \le 1.79, p_{\rm s} \ge 0.15.$ 

#### RT2

The main effect of SOA was significant, F(3,114) = 450.126, p < 0.001,  $\eta_p^2 = 0.92$ , reflecting the typical PRP effect with steeply increasing reaction times as SOAs get shorter (Pashler, 1994). Post hoc analyses revealed significant differences between all SOAs,  $p_s < 0.001$ . The main effect of Response Compatibility was significant too, F(1,38) = 90.394, p < 0.001,  $\eta_p^2 = 0.70$ , indicating faster RTs for compatible trials (M = 563, SEM = 10.9) than for incompatible trials (M = 642, SEM = 15.7). This effect varied as a function of SOA, as indicated by a significant Response Compatibility × SOA interaction, F(3,114) = 50.681, p < 0.001,  $\eta_p^2 = 0.57$ . Post hoc analyses revealed that the RCE was significant for SOAs 40, 130, and 300 (155, 104, and 45 ms, respectively,  $p_{\rm s} < 0.001$ ), but not for the SOA-900 (11 ms, p = 0.91). There was no other significant effect,  $F_s \le 1.79$ ,  $p_s \ge 0.36$ .

# Physiological and Mood Measurements

ANOVAs showed a main effect of time for pleasure,  $F(1,38) = 8.792, p = 0.005, \eta_p^2 = 0.19$ , arousal F(1,38) = 11.868, p = 0.001,  $\eta_p^2 = 0.24$ , and HR, F(1,38) = 9.727, p = 0.003,  $\eta_p^2 = 0.20$ , but not for SBP and DBP,  $F_s < 1$ ,  $p_s \ge 0.43$ . Pleasure, arousal and HR levels decreased during the experiment [Pleasure:  $M_{\text{Time 1}} = 1.6$  ( $SEM_{\text{Time 1}} = 0.2$ ) vs.  $M_{\text{Time 2}} = 1.1$  $(SEM_{Time 2} = 0.2)$ ; Arousal: 0.6 (0.2) vs. -0.4 (0.3); HR: 86.0 (2.4) vs. 77.5 (2.3)], whereas SBP [124.0 (2.4) vs. 122.5 (2.8)] and DPB [72.4 (1.4) vs. 72.8 (2.0)] did not vary across time. Importantly, neither the group effect nor the interaction was significant,  $F_s \leq 2.6$ ,  $p_s \geq 0.11$ , suggesting that physiological and mood changes were comparable across groups: Pleasure [Control: 1.4 (0.2) vs. 1.1 (0.3); Gamma: 1.9 (0.2) vs. 1.1 (0.3)], arousal [Control: 0.5 (0.3) vs. -0.7 (0.4); Gamma: 0.7 (0.3) vs. -0.1 (0.4)], HR [Control: 89.3 (3.4) vs. 79.8 (3.3); Gamma: 82.7 (3.4) vs. 75.2 (3.3)], SBP [Control: 120.3 (3.4) vs. 120.3 (3.9); Gamma: 127.8 (3.4) vs. 124.8 (3.9)] and DBP [Control: 71.5 (2.0) vs. 74.8 (2.8); Gamma: 73.2 (2.0) vs. 70.9 (2.8)]. This suggests that we can rule out an account of our results in terms of physiological and/or mood changes.

### **DISCUSSION**

We tested the possibility that high-frequency binaural beats in the gamma range bias cognitive control toward more flexibility. We hypothesized that this would induce more crosstalk between the two tasks in a dual-task paradigm, resulting in a more pronounced RCE in the first task after being exposed to gamma beats than in a control condition. The findings show the predicted result and there was no indication that mood or other physiological changes were responsible for, or related to this effect (even though we acknowledge that a possible moderation

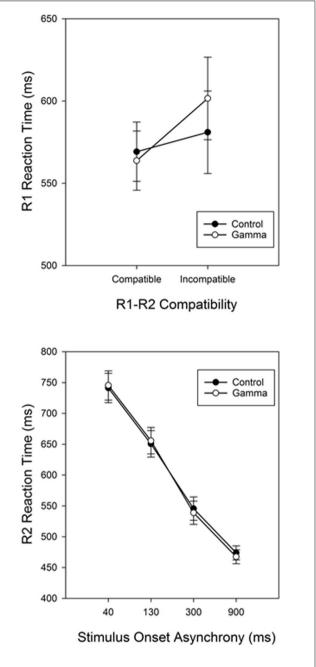


FIGURE 1 | Response-compatibility (R1-R2 Compatibility) effect in Task 1 (RT1) for the control and gamma groups (top panel). Reaction times for Task 2 (RT2) as a function of group (control vs. gamma) and stimulus onset asynchrony (bottom panel). Error bars represent standard errors of the response-compatibility effect (Task 1) and the PRP effect (Task 2).

by mood need not be inconsistent with our prediction, as both cognitive control and mood rely on dopaminergic supply and are thus sensitive to changes therein: e.g., Akbari Chermahini and Hommel, 2012). We thus consider the present findings to support the assumption that gamma beats promote cognitive flexibility. This has both theoretical and practical relevance, as it shows that control states can be affected and be systematically biased by

TABLE 1 | Reaction times (in ms) for Task 1 (RT1) and Task 2 (RT2) as a function of group (control and gamma), response-category compatibility (R1-R2 compatibility), and stimulus onset asynchrony (SOA).

Task	Group	R1-R2 compatibility		:	SOA	
			40	130	300	900
RT1	Control	Compatible	560 (14.8)	573 (17.6)	585 (25.4)	559 (20.9)
		Incompatible	610 (30.2)	598 (25.6)	566 (26.1)	551 (24.4)
			50	25	-19	-8
	Gamma	Compatible	561 (14.8)	573 (17.6)	564 (25.4)	557 (20.9)
		Incompatible	647 (30.2)	634 (25.6)	559 (26.1)	566 (24.0)
			87	60	-5	9
RT2	Control	Compatible	668 (17.0)	605 (18.1)	527 (19.1)	468 (12.5)
		Incompatible	815 (33.9)	696 (26.6)	564 (20.4)	480 (11.4)
			147	91	37	12
	Gamma	Compatible	663 (17.0)	595 (18.1)	513 (19.1)	462 (12.5)
		Incompatible	827 (33.9)	716 (26.6)	565 (20.4)	473 (11.4)
			164	121	52	11

Standard errors of the means are presented in parenthesis.

task-irrelevant stimulation. This seems to suggest that cognitivecontrol states can be triggered exogenously, which challenges the traditional idea that stimulus processing and response selection emerges from the competition between endogenous control operations and exogenous, stimulus-induced tendencies (e.g., Verbruggen et al., 2014). On the positive side, our findings suggest that binaural beats provide the opportunity for cognitive enhancement by providing people with tools to tailor their cognitive-control states to situational demands. In particular, binaural beats seem to provide the opportunity to increase people's cognitive flexibility in a rather automatic fashion, that is, without any particular instruction or task-relevance of the beats. We note that our sample is predominantly female, a common limitation for studies using psychology students as participants. On the one hand, the two experimental groups were matched for gender, so that this general gender imbalance cannot account for our main findings. On the other hand, however, more research will be necessary to see whether these findings generalize to males.

Before speculating on the possible neural mechanisms underlying the impact of binaural beats, we would like to discuss a recent finding that does not seem to fit with our flexibility hypothesis. In particular, Colzato et al. (2015) observed that binaural gamma beats reduced the global-precedence effect in a Navon task (i.e., better performance to the global than to the local features of a visual stimulus) and interpreted this finding in terms of a stronger and/or more efficient focusing of attention on the relevant dimension. One possible implication of this finding could be that binaural gamma beats affect the choice between alternative interpretations of the same stimulus (as in the Navon task) differently than the choice between alternative stimulus events (as in Reedijk et al., 2015), alternative verbal concepts (as in Reedijk et al., 2013), and alternative responses (as in the present task). For instance, focusing visual attention on global features relies on information from different frequency channels than focusing on local features (Hills and Lewis, 2009) and it might be impossible to process both kinds of information at the same time. Another possibility is that a less pronounced globalprecedence effect actually represents a broader distribution of resources rather than more focusing. Global precedence might reflect an unequal distribution of attentional resources to the benefit of global information (Robertson, 1996), a rather strong focus that is, so that a reduction of the precedence effect reflects a more equal distribution. If so, the findings from the Navon task would fit reasonably well with our flexibility hypothesis. In any case, the question whether the flexibility hypothesis also holds for the processing and selective attention to global and local features of visual stimuli requires further study.

More research will also be needed to better understand the neural mechanisms underlying both the perceptual illusion that binaural beats induce and the way they affect cognitive-control states. The impact of auditory stimulation on cognitive control is unlikely to be a result of local cortical priming or interactions but rather seems to point neural communication at a larger scale. Larger-scale neural communication has been argued to rely on brain rhythms (Fries, 2009; Brunet et al., 2014), which might be sensitive to binaural beats of particular frequency bands. Indeed, recent studies have shown that beat stimulation affects functional brain connectivity (Gao et al., 2014) and modulates intracranial power and phase synchronization (Becher et al., 2015). These findings support the idea that the impact of binaural beats on cognitive processes might be mediated by neural phase locking (Karino et al., 2006; see, Chaieb et al., 2015, for a recent review on the effect of binaural beats on cognition and mood), in the sense that the beats induce or entrain a particular neural pattern that promotes or impairs neural communication underlying particular cognitive processes, such as cognitive control. Hence, binaural beats may act as a neural entrainment technique that operates by modulating the brain oscillations that particular cognitive processes require or benefit from, and oscillations in the gamma-frequency band might be particularly relevant for this purpose (Pastor et al., 2002; Schwarz and Taylor, 2005). To test that, future studies may make use of electroor magneto-encephalographic methods, which would permit assessing the relationship between binaural beats and the auditory entrainment of brain oscillations (e.g., Galambos et al., 1981; Picton et al., 1987) and the role of oscillations in the gamma range for local brain communication (Kopell et al., 2000; Quilichini et al., 2010) more directly. Pharmacological studies would also be useful to test, for instance, the possibility that binaural beats involve norepinephrine/glutamate dynamics and increase phasic norepinephrine to enhance cognitive processing (Mather et al., 2015).

In any case, our findings suggest three main conclusions. First, they provide converging evidence for the idea that the current metacontrol state, which we argue implements a particular degree of persistence versus flexibility of cognitive control, can be systematically biased. This supports the general idea that control processes can vary in style (e.g., Goschke, 2003; Cools and D'Esposito, 2011; Hommel, 2015) and the assumption that inducing particular internal states provides an effective means to promote particular styles (e.g., Dreisbach and Goschke, 2004). Second, our findings provide converging evidence for the idea that binaural beats in the gamma range have an impact on the current metacontrol state. While the functional and neural mechanism underlying this impact is not yet entirely understood, the empirical link between the processing of rather lowlevel auditory stimuli and broadly operating control processes provides rather strong constraints on how this mechanism might work. The question how binaural beats affect brain rhythms related to cognitive control might be key in getting more insight on this issue. Third, together with our previous observations (Reedijk et al., 2013, 2015), the present findings point to some interesting commonalities of, and functional overlap between the selection and consolidation of successive visual stimuli, the sequential search of verbal stimuli in memory, and the separation of sequentially performed tasks. These commonalities seem to support Hommel's (2015) claim that metacontrol states operate on (i) the degree to which alternative representations compete with each other and (ii) the degree to which their mutual competition is top-down biased through the current goal. In particular, a tendency toward persistence would imply

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strong competition and top-down bias while a tendency toward flexibility would imply weak competition and top-down bias. If we assume that gamma beats reduce competition and top-down bias, this would explain why processing the second of two targets is less hampered by the first (Reedijk et al., 2015), why searching for multiple words related to the same concept is easier (Reedijk et al., 2013), and why response representations belonging to two different tasks show more crosstalk, as in the present study. Further studies will be necessary to investigate whether and to what degree the biasing of metacontrol states can affect not only the crosstalk between two tasks but also the efficiency to which they can be performed.

In the present study, we found crosstalk effects but no impact of binaural beats on the SOA effect on R2, which is considered to diagnose the bottleneck underlying multitasking. On the one hand, this dissociation between crosstalk and multitasking effects might be taken to challenge the claim that multitasking costs reflect inter-task crosstalk (Navon and Miller, 1987). On the other hand, however, it is still possible that the bottleneck underlying multitasking costs is functional, rather than structural, in nature and that the respective serial processing style is chosen to minimize crosstalk (Miller et al., 2009). In fact, it is possible that increasing crosstalk provides even stronger motivation to serialize as many (other) processes as possible, even though the size of our crosstalk effect might have been too small to make that visible in the SOA effect. To investigate these possibilities more systematically, it would seem to make sense to choose more powerful manipulations to target metacontrol states than those provided by binaural beats, but we leave that to future studies.

# **AUTHOR CONTRIBUTIONS**

Authors LC and BH designed the study and wrote the protocol. Authors RS, RF, and SB managed the literature searches and analyses. Author SB collected the data. Authors LC, BH, and RS wrote the first draft of the manuscript. All authors contributed to and have approved the final manuscript.

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# Transferability of Dual-Task **Coordination Skills after Practice** with Changing Component Tasks

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Recent research has demonstrated that dual-task performance with two simultaneously presented tasks can be substantially improved as a result of practice. Among other mechanisms, theories of dual-task practice-relate this improvement to the acquisition of task coordination skills. These skills are assumed (1) to result from dual-task practice, but not from single-task practice, and (2) to be independent from the specific stimulus and response mappings during the practice situation and, therefore, transferable to new dual task situations. The present study is the first that provides an elaborated test of these assumptions in a context with well-controllable practice and transfer situations. To this end, we compared the effects of dual-task and single-task practice with a visual and an auditory sensory-motor component task on the dual-task performance in a subsequent transfer session. Importantly, stimulus and stimulus-response mapping conditions in the two component tasks changed repeatedly during practice sessions, which prevents that automatized stimulus-response associations may be transferred from practice to transfer. Dual-task performance was found to be improved after practice with the dual tasks in contrast to the single-task practice. These findings are consistent with the assumption that coordination skills had been acquired, which can be transferred to other dual-task situations independently on the specific stimulus and response mapping conditions of the practiced component tasks.

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#### INTRODUCTION

Performing two component tasks simultaneously at the same time (i.e., dual tasks) can be extremely difficult but this difficulty is often reduced after practice. For example, during the first lessons of driving school students find it challenging to coordinate the large number of different activities and components of car driving (e.g., changing gear, lane change, navigation, etc.). At the end of the lessons students are, however, able to coordinate these activities enabling them to drive safely in road traffic. In other words, an improved coordination of multiple task requirements may result from ongoing practice and may lead to improved performance in dual-task-like situations of car driving at the end of practice. However, while this example illustrates a plausible every day situation of practice-related improvement in dual-task coordination, findings in the literature are not conclusive concerning empirical evidence for the acquisition of task coordination skills to explain dual-task improvement.

The present study tackles this issue, assessing whether task coordination skills are acquired with dual-task practice and whether this represents a mechanism underlying improved dualtask performance, which may explain practice-related reduction of dual-task costs. The improvement of task coordination skills is typically associated with an optimized control of two simultaneous task processing streams in dual-task situations (Hirst et al., 1980). From a learning perspective, it is important to know whether there is evidence for such skill acquisition (Anderson, 1988; Taatgen, 2013) in the context of complex situations (i.e., situations with two simultaneous tasks). Such evidence would be important for learning accounts assuming that task coordination skills can be acquired during dual-task training and that these skills are assumed to affect the practicerelated improvement of dual-task performance in addition to task automatization (Schneider and Shiffrin, 1977; Logan, 1988) or learning of the component tasks during dual-task practice (Ahissar et al., 2001; Ruthruff et al., 2006; Maquestiaux et al., 2008; Strobach et al., 2013; Strobach and Schubert, 2017).

#### **Prior Tests of Task Coordination Skills**

According to theoretical considerations, task coordination skills are acquired and improved under dual-task practice conditions, but not when practicing each task in isolation under singletask practice conditions (Hirst et al., 1980; Kramer et al., 1995; Strobach et al., 2014). That is, these skills evolve from practicing two tasks simultaneously, rather than being attributable to learning the component tasks (Damos and Wickens, 1980; Oberauer and Kliegl, 2004; Silsupadol et al., 2009). Furthermore, once acquired, improved task coordination skills should at least be partially independent of the specific properties of the component tasks presented during dual-task practice. Consequently, these skills should be (at least to some extent) transferable across different dual-task situations (Kramer et al., 1995; Bherer et al., 2006; Liepelt et al., 2011).

Several studies have provided preliminary evidence, which supports the assumption that under certain conditions task coordination skills can indeed be acquired during long lasting training. As an example, studies testing the consequences of experience with dual tasks in comparison with the consequences of single task training were conducted in persons having extensive experience in playing a particular type of video games, known as action video games and its common subgenre ego-shooters. These games typically require the fast performance of several actions such as follow and maintain aims of the game, fight enemies, locate supplies, etc. The actions are performed under extreme temporal processing demands either at the same time or within close temporal proximity during the games. In contrast to persons without game experience, action video gamers show an optimized ability to perform and coordinate two simultaneous tasks in a dual-task paradigm of the Psychological Refractory Period (PRP) type (Pashler, 1994; Schubert, 1999) including well-controllable sensorimotor tasks (e.g., Strobach et al., 2012c; Chiappe et al., 2013).

Further evidence suggesting that task coordination skill may differ between persons with different degree of multitasking experience, stems from studies comparing the dual-task performance of highly skilled simultaneous interpreters and control participants. Simultaneous interpreting is an activity that is highly complex and requires the performance of multiple simultaneous tasks. Among others, these tasks include the analysis and understanding of the discourse in a first language, reformulating linguistic material, language production in a second language, and storing of intermediate processing steps. In two studies, we explored whether persons with experience in simultaneous interpreting possess superior skills in coordination of multiple tasks and whether they are able to transfer these skills to PRP dual tasks (Strobach et al., 2015a; Becker et al., 2016). In fact, we found faster dual-task reaction times (RTs) in persons with experience in simultaneous interpretation in contrast to control participants without such experience. Thus, action video gamers and simultaneous interpreters seem to possess superior skills to coordinate multiple tasks in lab-based dual-task situations. However, both cases, action video gaming as well as simultaneous interpreting, are no well-controllable practice situations and, therefore, do not allow for a systematic analysis of the specific underlying mechanisms and practice components as well as of the amount of practice enabling the acquisition of task coordination skills. For instance, in the context of video games, the number and frequency of situations with the presentation of simultaneous tasks is uncontrolled, so are the types of tasks combined. Further, it might be the sheer complexity of the situations (i.e., the combination of multiple tasks in action video games or during simultaneous interpreting without temporal overlap of these tasks), but not the experience of simultaneous tasks per se, that had led to the acquisition of task coordination skills (Schneider et al., 2002).

Recently, several studies proposed a well-controllable situation of dual-task practice, which is promising to investigate the characteristics of task coordination skill acquisition (Liepelt et al., 2011; Strobach et al., 2012d). In that situation, two groups of participants experience different types of practice with two sensorimotor component tasks, a visual-manual (i.e., the visual task) and an auditory-verbal tasks (i.e., the auditory task). In the visual task, there were spatially compatible mappings of circle positions on the screen to manual finger responses. In the auditory task, different tone pitches (low, medium, high) had a compatible mapping on number words ("ONE," "TWO," "THREE"). While hybrid practice included single-task and dual-task trials (see also Schumacher et al., 2001; Strobach et al., 2015b), single-task practice included single-task trials alone. After extended practice the authors compared the performance of the two different practice groups, i.e., the single-task and the hybrid practice groups, in a dual-task transfer situation in which the auditory and the visual task were processed simultaneously. In fact, after hybrid practice dual-task performance was better than after single-task practice.

Importantly, the studies could demonstrate an improvement after hybrid practice, which was exclusively realized by reduced dual-task RTs in the auditory task while there was no evidence for a hybrid practice advantage in the visual task. This is important because the auditory task was processed more slowly as compared to the visual task (see also Schumacher et al., 2001; Tombu and Jolicoeur, 2004; Hartley et al., 2011; Strobach et al., 2012a,b).

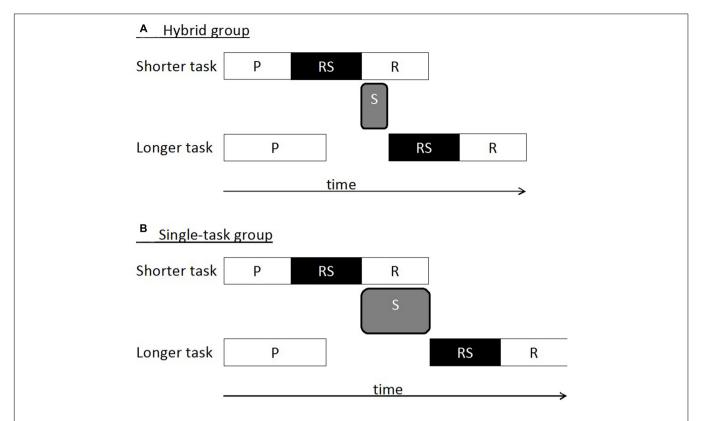


FIGURE 1 | Dual-task processing architecture after hybrid practice (A: Hybrid group) and single-task practice (B: Single-task group). According to bottleneck models, central response-selection (RS) stages are processed sequentially even with task practice (Maquestiaux et al., 2004; Ruthruff et al., 2006) while perception (P) and response (R) stages are processed in parallel. A potential switching stage (S) after the response-selection (RS) stage in the shorter task and before the RS stage in the longer task is shortened after hybrid in contrast to single-task practice. The latter phenomenon is a promising candidate to explain reduced dual-task costs after having experience with dual tasks (i.e., hybrid practice). Note that the latencies of the individual processing stages (i.e., P, RS, S, R) in the figure are schematic illustrations and may not represent actual stage latencies.

The authors proposed a model, which is illustrated in Figures 1A,B, to explain the observation of the hybrid-practice advantage in the longer auditory task but not the shorter visual task. As can be seen in the related figures, the model is based on the well-known assumption that sensorimotor tasks can be separated into an initial perception stage, a central response-selection stage and a final motor stage. According to the prominent central bottleneck model, the perception and motor stages in two tasks run in parallel while the central response-selection stages of such tasks are capacity-limited and represent bottleneck processes. This capacity limitation requires the serial processing of these stages and their coordination. Figure 1A illustrates the assumption that dual-task processing can be considered as the sequence of a capacity limitation in the faster visual task (e.g., at a central response-selection stage) followed by a switching operation between the responseselection stages, and the capacity limitation in the slower auditory task (Lien et al., 2003; Band and van Nes, 2006; Schubert, 2008). The switching operation is theorized as activating and/or instantiating the rules that map the stimuli of the longer task onto responses (Maquestiaux et al., 2004). It may be that these rules must be moved back into working memory or that the rules remaining in working memory throughout the task must

be reestablished during ongoing processing of task 1 and task 2. After hybrid practice (**Figure 1A**) in contrast to single-task practice (**Figure 1B**), activation/instantiation processes are highly efficient due to task coordination skills, leading to a more efficient and therefore faster switching operation; in other words, participants have learned to load task information faster or more efficiently into the working memory as a result of hybrid practice. Therefore, improved dual-task performance after hybrid practice may occur in the longer auditory task, because the shortened switching operation is located between the response-selection stages in the faster visual task and the slower auditory task (Strobach et al., 2014, for a more detailed discussion).

Essentially, the conclusion of a shortened switching operation as an explanation for the findings of Liepelt et al. (2011) and Strobach et al. (2012d) can be distinguished from other explanations focusing on task automatization and/or stage shortening within the component tasks (Ruthruff et al., 2006; Strobach et al., 2013). This is so because, participants of the hybrid and single-task practice groups received the identical number of stimulus contacts and, thus, of experience with each component task during practice. In addition, the performance in the single visual task and single auditory task was similar across groups after single and hybrid practice. This makes it implausible

from a methodological perspective as well as from a results perspective to assume that differences in single-task performance between the training groups can explain the findings of Liepelt et al. (2011) and Strobach et al. (2012d).

Nevertheless, several methodological aspects of the findings of Liepelt et al. (2011) and of Strobach et al. (2012d) require further elucidation of the assumption that hybrid practice with the current type of component tasks can lead to the acquisition of transferable task coordination skills. This is so because in these studies the advantage after hybrid practice in the auditory task was evident when the authors analyzed the dualtask performance in a specific transfer situation, which was presented to the participants after the final training session. More specifically, in the studies of Liepelt et al. (2011) and Strobach et al. (2012d) the dual-task situation in the transfer session was either completely identical to the practiced situation, or it consisted of at least one unchanged but practiced component task while the other component task had changed from practice to transfer; note that in different experiments either the visual or the auditory task remained unchanged from practice to transfer.

The authors interpreted these findings (i.e., transfer in conditions with one task changed while the other task remained unchanged) as evidence for the assumption that task coordination skills are not tied to specific characteristics of the practiced component tasks (Liepelt et al., 2011; Strobach et al., 2012d). While this assumption was based on the fact that transfer was found either in a situation in which the auditory component task had changed and in a different situation in which the visual task had changed from training to transfer, one cannot completely be sure that the observed findings indeed showed the existence of task coordination skills that are unspecific to the two component tasks. Thus, it might be the case that the acquired task coordination skills are tied to either of the two component tasks in a dual-task situation and only one constant task after practice might be sufficient for a successful application of acquired coordination skills during transfer. Note that a situation with at least one unchanged task remaining constant between training and transfer might allow for precisely predicting the time durations when the processes of a component task need to be started in a dual-task situation and/or are expected to be finished; this might produce a benefit for the transfer of coordination skills after practice. We know from investigations on time duration production skills, that transfer from practiced to un-practiced time durations is impaired when a secondary task presented during practice was removed during the transfer test (Healy et al., 2005).

In sum, prior studies lack convincing empirical evidence for the existence of task coordination skills, which can be transferred in task contexts with two changing component tasks during training of well-controllable task and training situations. The aim of the present study is to fill this gap in the dual-task practice literature.

Findings of earlier studies are tempting to assume that an increase in the variability of the practiced learning examples in alternative practice situations may enforce skill transferability after practice (Schmidt and Bjork, 1992; but see Logan, 1990). For instance, the transferability of duration production skills to un-practiced durations were increased after variable practice with mixed durations in contrast to blocked sequences of trials all of the same duration in the study of Schneider et al. (1995). Therefore, in the current study, the specific stimulus and stimulus-response rules of both, i.e., of the visual and of the auditory tasks (Liepelt et al., 2011) were changed between every second practice sessions to increase the variability of the learning examples during practice; this should enforce the need to train general task coordination skills but not specific task automatization.

One group of participants trained the two tasks in 15 hybrid dual-task training sessions and these participants were tested in a final transfer Session 16 at the end of practice. A further group of single-task learners trained the two tasks in single task regimen and were also tested for dual-task performance in this transfer session; these participants also experienced the two session-wise changes of the stimuli and the stimulus-response rules of the component tasks, i.e., the specific character of the visual and auditory tasks was changed between practice sessions equivalently to the changes in the hybrid group. Importantly, the single-task group, had experience only with single-task trials during the 15 practice sessions before the final transfer Session 16. Based on the assumption that an increase in variability increases the chances for transfer of task coordination skills, we predict improved dual-task performance in transfer Session 16 after variable hybrid practice than after single-task practice.

#### MATERIALS AND METHODS

## **Participants**

Participants were randomly assigned to one of the two experimental groups: the hybrid group and the single-task group. In line with previous dual-task learning studies (Liepelt et al., 2011; Strobach et al., 2012d), we included eight participants (six female) with a mean age of M = 24.5 years (SD = 3.5 years) and an age range from 19 to 29 years in the hybrid group. Eight participants (five females) were included in the single-task group with a mean age of M = 23.8 years (SD = 3.2 years, age range from 19 to 28 years). According to the experience from earlier training studies (Liepelt et al., 2011; Strobach et al., 2012d), the administration of frequently changing stimulusresponse rules should require a large number of training sessions in order to get reliable training-related improvements in task performance. A group size of eight participants in each group allows bringing together the requirements for an increased number of training sessions with the requirements of feasible experimental economics (Schubert and Strobach, 2012). Furthermore, an additional analysis with G\*Power (Faul et al., 2007) using values of previous training studies (Liepelt et al., 2011; Strobach et al., 2012d) has shown that a group size of eight participants per group will provide sufficient power (>0.9) with an alpha set at 0.05. The two groups performed altogether 16 sessions, which represents a volume of 256 h of experimentation. All participants of these groups were included into the final data set. Participants were contacted through flyers and electronic mails. All participants had normal or corrected to normal vision

and were not informed of the purpose of the experiment. They were paid for participation at a rate of 8€ per session plus performance-based bonuses.

# **Apparatus**

Visual stimuli were presented on a 17-inch color monitor and auditory stimuli were presented via headphones, which were connected to a Pentium I IBM-compatible PC. The RT for manual responses was recorded with a button box and the RT of verbal responses was recorded via a voice key connected to the experimental computer. The experimenter typed the actual response on a computer keyboard so that accuracy could be assessed in the analysis. The experiment was controlled by the software package ERTS (*Experimental Runtime System*; Beringer, 2000).

# **Stimuli and Component Tasks**

During Sessions 1-16, participants conducted different versions of visual and auditory sensorimotor tasks. All tasks and versions were three-choice tasks and included mappings between 3 stimuli and 3 responses. In the visual task versions, all visual stimuli were white and participants responded with their index, middle, and ring finger of their right hand in accordance to the following lists of stimuli as illustrated in Figure 2: circles appearing at the left, central, or right screen position (Sessions 1, 2, 8, and 16), squares appearing at the left, right, or central positions (Sessions 3 and 4), a circle, square, and triangle appearing at the central position (Sessions 5 and 6), a line pattern, semicircle, and cross appearing at the central position (Sessions 7 and 15), triangles of large, medium, and small size appearing at the central position (Sessions 9 and 10), a right-, left-, or top-oriented opening in a square appearing at the central position (Sessions 11 and 12), and a diamond appearing at vertical top, central, and bottom positions (Sessions 13 and 14). In the auditory task versions, participants responded with the verbal number words "ONE," "TWO," and "THREE" in accordance to the following stimuli (Figure 2): a low, middle, and high sine-wave tone (Sessions 1, 2, 8, 9, 10, and 16), a low high-pitched, middle high-pitched, and high high-pitched sine-wave tone (Sessions 3 and 4), a whistling sound, middle sine-wave tone, and buzzer tone (Sessions 5 and 6), a "wup"-like sound, signal sound, and clicking noise (Sessions 7 and 15), high white noise, middle sine-wave tone, and low drum sound (Sessions 11 and 12), white noise, middle "wup"like sound, and high "djing"-like sound (Sessions 13 and 14). We selected these sets of stimulus and response mappings across the visual and auditory tasks and the experimental sessions, because these mappings significantly differ from each other and thus increased variability on the one hand (e.g., stimulus-response mapping rules were compatible, incompatible, and arbitrary). On the other hand, we assumed that participants were able to perform these mappings after only a short introduction.

In visual single-task trials, three white dashes served as placeholders for the possible positions of the visual stimuli. They appeared as a warning signal 500 ms before the visual stimulus was presented. The stimulus remained visible until the participant responded or a 2,000 ms response interval had expired. After correct responses, RTs were presented for 1,500 ms

on the screen. Following incorrect responses, the word "ERROR" (German: "FEHLER") appeared. A blank interval of 700 ms preceded the beginning of the next trial. An auditory single-task trial started with the presentation of three dashes on the computer screen. After an interval of 500 ms, the tones were presented. The trial was completed when the participant responded verbally or a 2,000 ms response interval had expired. To acquire an accurate measurement of verbal responses, the experimenter typed the actual response on a computer keyboard so that accuracy could be assessed in the analysis. After verbal responses, RTs were presented for 1,500 ms on the screen. Following omitted verbal responses, the word "ERROR" (German: "FEHLER") appeared. A blank interval of 700 ms preceded the beginning of the next trial. Dual-task trials included the visual and the auditory task. These trials were identical to single-task trials with the exception that a visual and an auditory stimulus were presented simultaneously (SOA = 0 ms). As in previous studies on a similar dual-task procedure, participants were not told to respond in any particular order and they should give equal priority to the two tasks. Instructions were designed to encourage participants to perform the tasks as quickly and accurately as possible in all trials and blocks.

# **Design and Procedure**Hybrid Group

This group performed hybrid practice in Sessions 1–16. Each session lasted <60 min and these sessions were conducted on consecutive days (except weekends). During hybrid practice, there were single-task trials and dual-task trials. Single tasks of the visual or the auditory task were included into single-task blocks of 45 trials. In contrast, 18 dual-task trials were included into mixed blocks combined with 30 mixed single-task trials, 15 of the visual task and 15 of the auditory task. These mixed single-task trials helped to ensure that participants were equally prepared for both tasks in mixed blocks; alternatively, they could prepare for only one task that is executed first in dual-task trials. Participants were instructed to respond to both stimuli as quickly and accurately as possible during all blocks. Response order was free.

In Session 1, participants of the hybrid group performed six visual and six auditory single-task blocks that were presented in alternating order (**Table 1**). Half of the participants started with a visual single-task block and the other half with an auditory single-task block. Session 2 included six single-task blocks (three visual and three auditory task blocks) and eight mixed blocks. After two initial single-task blocks (one visual and one auditory single-task block), sequences of two mixed blocks and one single-task block followed; the type of single-task blocks was alternated. The order of blocks (first visual or auditory task block) was counterbalanced across participants. The design in Sessions 3–16 was identical to that in Session 2 but these sessions included two additional mixed blocks at the end.

#### Single-Task Group

The experimental procedure in the single-task group was similar to the hybrid group with the exception that this group of participants performed single tasks (almost) exclusively in Sessions 1–15 (**Table 1**). To keep the number of stimulus contacts

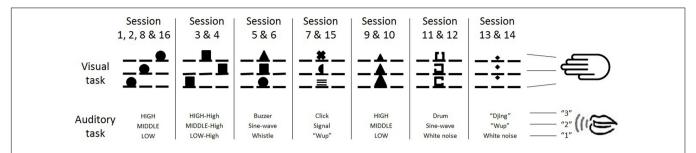


FIGURE 2 | Illustration of the stimulus-response mapping characteristics of the visual and auditory tasks in the hybrid and single-task group across Sessions 1–16. See main text for further details on these characteristics.

**TABLE 1** Illustration of the training regime across 16 sessions in the hybrid group/single-task group.

		Session		
Block	1	2	3–15	16
1	s-short/s-short	s-short/s-short	s-short/s-short	s-short/s-short
2	s-short/s-short	s-short/s-short	s-short/s-short	s-short/s-short
3	s-short/s-short	mix/mix	mix/s-long	mix/mix
4	s-short/s-short	mix/mix	mix/s-long	mix/mix
5	s-short/s-short	s-short/s-short	s-short/s-short	s-short/s-short
6	s-short/s-short	mix/s-long	mix/s-long	mix/mix
7	s-short/s-short	mix/s-long	mix/s-long	mix/mix
8	s-short/s-short	s-short/s-short	s-short/s-short	s-short/s-short
9	s-short/s-short	mix/s-long	mix/s-long	mix/mix
10	s-short/s-short	mix/s-long	mix/s-long	mix/mix
11	s-short/s-short	s-short/s-short	s-short/s-short	s-short/s-short
12	s-short/s-short	mix/s-long	mix/s-long	mix/mix
13		mix/s-long	mix/s-long	mix/mix
14		s-short/s-short	s-short/s-short	s-short/s-short
15			mix/s-long	mix/mix
16			mix/s-long	mix/mix

s-short and s-long indicate short single-task blocks (45 trials) and long single-task blocks (66 trials), respectively, of either the visual or the auditory task. mix illustrates mixed blocks (including 15 visual single-task trials, 15 auditory single-task trials, and 18 dual-task trials).

between dual-task conditions (in the hybrid group) and singletask conditions constant, one dual-task trial was replaced by one single-task trial of each task. Consequently, we had singletask blocks with 45 trials (short blocks) or 66 trials (long blocks). Session 1 was identical to the hybrid group. Session 2 included 12 single-task blocks (six visual and six auditory task blocks). Importantly, this session also included two mixed blocks. These mixed blocks were included to analyze initial dual-task performance in the single-task practice group before practice and to match this performance between practice groups. In Session 2, these two initial mixed blocks were introduced after two short single-task blocks. Then, sequences of one short and two long single-task blocks followed. In Sessions 3-15, we presented 16 single-task blocks (eight visual and eight auditory task blocks). After two initial short single-task blocks, sequences of two long single-task blocks and one short single-task block followed. In Sessions 2-15, blocks with the visual and auditory task were alternated and the first type of block (either visual or auditory task) was counterbalanced between subjects. The following Session 16 was identical to this session in the hybrid group.

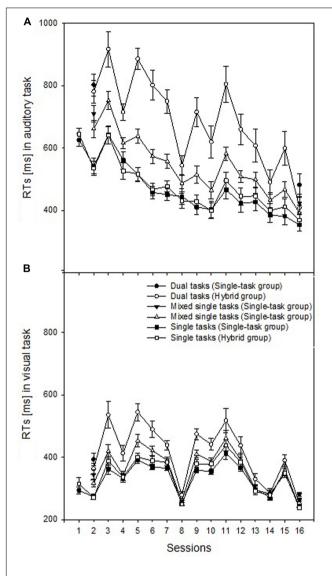
#### **RESULTS**

# **Statistical Analyses**

We excluded all trials in which responses were omitted or incorrect (7.0%) prior to statistical RT analyses. The alpha level for significant effects and interaction was set to p=0.05. Effects sizes were illustrated with partial  $\eta^2$  for significant main effects and interactions.

To obtain a strong and reliable parameter for dual-task performance, we assessed dual-task performance in dualtask trials and single tasks of single-task blocks: dualtask costs = Performance<sub>dual-task trials</sub> - Performance<sub>single-task</sub> trials of single-task blocks (Tombu and Jolicoeur, 2004; Strobach et al., 2015c). This parameter of dual-task costs is particularly essential when investigating task coordination skills (Liepelt et al., 2011; Strobach et al., 2012d). It combines trials that are by definition not related to each other (i.e., pure single-task trials and dualtask trials) and is therefore most informative to investigate task coordination skills. We thus excluded mixed single-task trials from the test on skill acquisition because processing associated with this type of trials is less specified. That is, participants will also be partially prepared for a task type that did not occur and this omission of an expected stimulus and task may have thrown off or surprised subjects (Tombu and Jolicoeur, 2004).

We focused on Sessions 2–15 to analyze hybrid practice performance; note that there were no dual-task trials included in Session 1. And we focused on Sessions 1–15 when comparing the single-task performance during hybrid and single-task practice. When testing the acquisition and transfer of task coordination skills, we analyzed single-task and dual-task performance during pre-test and post-test. For the pre-test, we analyzed the dual-task performance by comparing the data in the first two single-task blocks with that of the dual-task trials in the two following mixed blocks in Session 2 in both, the hybrid and the single-task group; note that also the single-task group performed two mixed blocks after two single-task blocks in the beginning of this session. The data of Session 16 (in which both the single-task



**FIGURE 3** | Reaction times (RTs) in millisecond (ms) of single-task trials in single-task blocks (Single tasks), single-task trials in mixed blocks (mixed single tasks), and dual-task trials (Dual tasks) for the single-task practice group (Single-task group) and the hybrid practice group (Hybrid group). **(A)** Auditory-task data; **(B)** Visual-task data.

and hybrid groups performed single and dual tasks) served as the post-test measure for the performance at the end of practice.

# Hybrid and Single-Task Practice Performance

The RT and error data of the practice sessions are illustrated in **Figure 3** and **Table 2**, respectively. To analyze dual-task performance in the hybrid group across practice, we included the within-subject factors Session (Sessions 2–15) and Trial type (dual tasks vs. single tasks) in mixed measures ANOVAs. The single-task and dual-task RTs varied as an effect of changes in the stimulus-response mapping characteristics and hybrid

practice in the auditory task, as indicated by main effects of Session F(13.91) = 28.530, p < 0.001,  $\eta_p^2 = 0.80$ , and Trial type, F(1,7) = 62.459, p < 0.001,  $\eta_p^2 = 0.90$ , as well as the interaction,  $F(13,91) = 16.801, p < 0.001, \eta_p^2 = 0.71$  (**Figure 3A**). The visual-task RTs showed a similar pattern with main effects of Session, F(13,91) = 31.710, p < 0.001,  $\eta_p^2 = 0.82$ , and Trial type,  $F(1,7) = 55.972, p < 0.001, \eta_p^2 = 0.89$ , as well as the interaction of Session and Trial type, F(13.91) = 5.028, p < 0.001,  $\eta_p^2 = 0.42$ (Figure 3B). Similar to the auditory-task RTs, this task's error rates also varied with hybrid practice and changes in the stimulusresponse mapping characteristics, as indicated by main effects of Session, F(13,91) = 5.502, p < 0.001,  $\eta_p^2 = 0.44$ , and Trial type, F(1,7) = 97.811, p < 0.001,  $\eta_p^2 = 0.93$ , as well as their interaction, F(13.91) = 6.823, p < 0.001,  $\eta_p^2 = 0.49$ . The visualtask error rates showed a similar pattern with main effects of Session, F(13,91) = 5.256, p < 0.001,  $\eta_p^2 = 0.43$ , and Trial type, F(1,7) = 11.767, p < 0.001,  $\eta_p^2 = 0.63$ , as well as the interaction,  $F(13,91) = 4.873, p < 0.001, \eta_p^2 = 0.41.$ 

To demonstrate similar levels of component-task processing skills during practice and transfer, we analyzed the singletask trials of single-task blocks in mixed measures ANOVA including the within-subjects factor Session (Sessions 1-15) and the between-subjects factor Group (hybrid group vs. single-task group); note that potential effects and interactions with Group were mainly relevant in these analyses. The auditory singletask RTs (Figure 3A) showed no main effect or interaction with Group, Fs < 0.913, ps > 0.545; Session demonstrated variable RTs across practice and changing task characteristics, F(1,14) = 66.456, p < 0.001,  $\eta_p^2 = 0.83$ . The error data in this task showed no main effect of and interaction with Group, Fs < 0.910, ps > 0.549; Session was significant, F(1,14) = 9.381, p < 0.001,  $\eta_p^2 = 0.40$  (**Table 2**). The visual single-task RTs (Figure 3B) produced no main effect of and interaction with Group, Fs < 0.910, ps > 0.549; Session demonstrated variable RTs across practice and changing task characteristics, F(1,14) = 69.854, p < 0.001,  $\eta_p^2 = 0.83$ . The main effect of and interaction with Group were also not evident in the error analysis of the visual task, Fs < 1.219, ps > 0.29; Session was significant, F(1,14) = 8.976, p < 0.001,  $\eta_p^2 = 0.38$  (**Table 2**). Thus, component-task processing skills did not statistically differ between both groups across practice.

#### Transfer Test on Task Coordination Skills

In this section, we compare the dual-task costs at the beginning of practice (i.e., pre-test: first two single-task blocks and dual-task trials of the first two mixed blocks in Session 2) and at the end of practice (i.e., post-test: single-task blocks and dual-task trials of the mixed blocks in Session 16) in the hybrid and the single-task group. Reduced dual-task costs and improved dual-task performance in the hybrid group, compared to the single-task group, during post-test would indicate the acquisition and transfer of improved task coordination skills if controlled for possible performance differences in the pre-test. In particular, as illustrated in **Figure 1**, the improved dual-task performance in the hybrid group is expected in the auditory task, because the

TABLE 2 | Error rates (in percent) across the auditory and visual tasks, the single-task, mixed single-task, and dual-task conditions, from Session 1 to Session 16 in the hybrid and single-task groups.

			Hybrid group	group					Single-task group	k group		
1		Auditory task			Visual task			Auditory task			Visual task	
Session	Single tasks	Mixed single tasks	Dual tasks	Single tasks	Mixed single tasks	Dual tasks	Single tasks	Mixed single tasks	Dual tasks	Single tasks	Mixed single tasks	Dual tasks
-	7.0			9.0			6.1			7.5		
2	4.4	5.6	11.6	2.0	9.0	4.3	4.3			1.8		
က	7.1	8.6	23.1	3.1	4.0	12.4	7.0			4.1		
4	4.7	9.6	13.9	3.4	2.6	4.5	6.1			3.2		
5	3.6	4.7	21.9	5.7	5.5	12.8	3.2			4.6		
9	3.4	3.1	12.4	4.0	3.2	8.1	3.9			4.1		
7	3.9	3.8	6.5	4.3	4.3	6.0	4.4			4.5		
∞	5.2	0.6	9.4	3.4	1.3	1.9	5.9			3.5		
6	5.6	5.8	17.1	7.8	7.6	8.5	5.8			6.2		
10	4.2	4.6	14.4	4.0	7.0	7.7	5.3			4.1		
11	9.9	5.6	20.5	7.9	6.5	12.3	9.9			5.2		
12	3.6	5.1	16.3	7.4	5.9	8.1	5.4			4.4		
13	6.4	7.2	13.1	5.5	4.6	5.6	8.1			4.0		
14	4.8	7.6	11.3	5.3	4.7	3.9	6.7			3.8		
15	5.2	6.3	4.4	6.8	7.7	7.2	5.4			4.6		
16	7.3	11.8	12.1	4.9	2.0	3.5	8.3	12.3	15.2	2.9	2.0	3.4

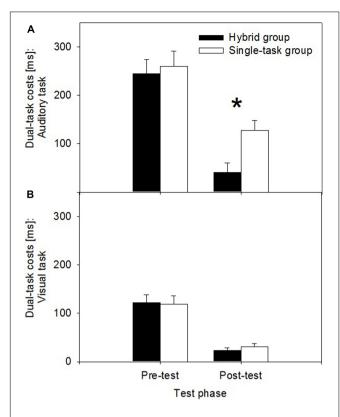


FIGURE 4 | Dual-task costs in millisecond (ms; dual-task RTs minus single-task RTs) during pre-test and post-test for the single-task practice group (Single-task group) and the hybrid practice group (Hybrid group).

(A) Auditory-task data; (B) Visual-task data. The asterisk denotes the significant difference.

anticipated speed-up switching operation is located between the central response-selection stages of the shorter visual and the longer auditory task. Thus, dual-task costs should be reduced at post-test after hybrid practice primarily in the auditory task and less so in the visual task. To test these assumptions, we performed mixed measures ANOVAs on the RT and error data with the within-subject factors Testphase (pre-test vs. post-test), Trialtype (single-task trials vs. dual-task trials), Task (auditory, visual task) and the between-subject factor Group (hybrid group vs. single-task group). This ANOVA revealed a significant fourway interaction, F(1,14) = 8.528, p = 0.01,  $\eta_p^2 = 0.38$ , for the RT data, suggesting changes in dual-task costs that differed between the auditory and the visual task. Accordingly, we conducted subsequent ANOVAs with the factors Testphase, Trialtype, and Group separately for the auditory and the visual task to assess whether the different types of practice led to changes in dual-task costs in these different tasks.

The RT results of the *auditory task* point to the acquisition and transfer of improved task coordination skills after hybrid practice. In fact, we found a three-way interaction between Testphase, Trialtype, and Group, F(1,14) = 12.671, p < 0.01,  $\eta_p^2 = 0.48$ . As illustrated in **Figure 4A**, at post-test, dualtask costs were significantly reduced after hybrid practice (M = 40 ms) in contrast to single-task practice (M = 110 ms),

t(14) < 2.135, p < 0.05. At pre-test, the difference between dual-task cost between the hybrid group and single-task group was not significant, t(14) = 1.305, p = 0.21. Thus, improved dual-task performance in the hybrid group at post-test cannot be explained by improved initial dual-task performance levels in this group relative to the single-task group. Furthermore, the improvement in dual-task performance is dual-task-specific, since it cannot be explained with differences in single-task RTs between groups, t(14) = 0.714, p = 49. The remaining effects and interactions in this RT analysis were as follows: Testphase, F(1,14) = 257.679, p < 0.001,  $\eta_p^2 = 0.95$ , Trialtype, F(1,14) = 150.129, p < 0.001,  $\eta_p^2 = 0.92$ , Group, F(1,14) = 0.046, p = 0.83, Testphase  $\times$  Trialtype, F(1,14) = 183.536, p < 0.001,  $\eta_p^2 = 0.93$ , Testphase × Group, F(1,14) = 1.123, p = 0.31, Trialtype × Group, F(1,14) = 0.057, p = 0.82. The error analysis of the auditory task showed no three-way interaction of Testphase, Trialtype, and Group, F(1,14) = 0.518, p = 0.49. The remaining effects and interactions in this analysis were as follows: Testphase, F(1,14) = 1.070, p=0.32, Trialtype,  $F(1,14)=51.683,\ p<0.001,\ \eta_p^2=0.79,$  Group,  $F(1,14)=1.104,\ p=0.31,$  Testphase  $\times$  Trialtype, F(1,14) = 3.646, p = 0.08, Testphase × Group, F(1,14) = 0.014, p = 0.91, Trialtype × Group, F(1,14) = 2.649, p = 0.13 (**Table 2**).

In order to test whether, the advanced dual-task performance (i.e., decreased dual-task costs) in the auditory task after hybrid practice compared to single-task practice is based on only a few participants with mean values strongly deviating from those of the rest, we conducted a non-parametric test on the dual-task RT costs in the auditory task. This test includes the rank of each participant according to its dual-task costs in the auditory task and it ignores the absolute dual-task costs. A non-parametric Mann–Whitney U test showed a significant difference between the ranks of the hybrid group (mean rank = 5.88) and the single-task group (mean rank = 11.13), p < 0.05 (lower rank value indicates a lower amount of dual-task costs). This result shows that the present finding of reduced dual-task costs after hybrid practice is not the result of only a few outlier participants.

In the visual task, there was no advantage in the RT data and thus no evidence for the acquisition and transfer of improved task coordination skills after hybrid practice. This conclusion results from the finding of a non-significant three-way interaction of Testphase, Trialtype, and Group, F(1,14) = 0.874, p > 0.37(**Figure 4B**). The remaining effects and interactions in this RT analysis were as follows: Testphase, F(1,14) = 80.229, p < 0.001,  $\eta_p^2 = 0.85$ , Trialtype, F(1,14) = 117.221, p < 0.001,  $\eta_p^2 = 0.89$ , Group, F(1,14) = 0.569, p = 0.46, Testphase  $\times$  Trialtype, F(1,14) = 49.712, p < 0.001,  $\eta_p^2 = 0.78$ , Testphase × Group, F(1,14) = 0.909, p = 0.36, Trialtype × Group, F(1,14) = 0.774, p = 0.39. Analogous, the error analysis of the visual task also showed no interaction of Testphase, Trialtype, and Group, F(1,14) = 0.153, p = 0.70. The remaining effects and interactions in this analysis on error rates in the visual task were as follows: Testphase, F(1,14) = 0.050, p = 0.84, Trialtype, F(1,14) = 3.630, p = 0.08, Group, F(1,14) = 0.035, p = 0.85, Testphase × Trialtype, F(1,14) = 7.177, p < 0.05,  $\eta_p^2 = 0.34$ , Testphase × Group, F(1,14) = 1.610, p = 0.23, Trialtype × Group, F(1,14) = 2.119, p = 0.17 (**Table 2**). In

sum, the present data pattern is consistent with the assumption of an acquisition of transferable task coordination skill and the assumption of a speed-up switching operation between tasks after hybrid practice.

# **Follow-Up Analyses**

At this point, critics may say that the transferable character of task coordination skills has not yet completely demonstrated. This is because the specific combination of component tasks in Session 16 was previously experienced in Sessions 1, 2, and 8. The dual-task performance advantage in the hybrid group may thus exclusively result from practice in these tree sessions and it might not result from learning processes during the other practice sessions and the related variations of the component tasks. To test this counter argumentation, we conducted a new group of 10 participants with single-task practice of eight sessions only. Importantly, the changes in the characteristics of the stimulusresponse mappings in these eight sessions were identical to the changes in the hybrid group's first eight sessions. In addition, this new single-task group had single-task practice in the first seven sessions (with the exception of a pre-test and its two mixed blocks in the beginning of Session 2) and performed single-task and mixed blocks in the final test Session 8. We compared the dual-task performance of this new single-task practice group with the dual-task performance of the hybrid training group in the 8th session. This comparison showed no main effect of Group and no interaction with Group for the analysis of the auditory-task RTs during pre-test and post-test under singletask and dual-task conditions, both Fs(1,18) < 2.402, ps > 0.14,  $\eta_p^2$ s < 0.15. This finding is important because it shows equal dual-task performance of the hybrid and the new single-task practice group after eight training sessions, which include the sessions with identical stimulus-response characteristics of the component tasks as those in Session 16 of the hybrid group. The fact that we could not find a difference between the new singletask and hybrid group at Session 8, but a significant difference in dual-task performance between the (initial) single-task and the hybrid group at Session 16, suggests the latter dual-task advantage has occurred because of the additional training sessions between Sessions 9 and 16. However, the trained component tasks during these additional training sessions, i.e., Sessions 9-15, did differ from the component tasks in Session 16. Therefore, we can conclude that the observed hybrid-practice advantage after 16 sessions cannot be explained by the repetition of the component task situation in Session 16 with that from the Sessions 1, 2, and 8. Differently to that participants of the hybrid-practice task have acquired skills from the training with task situations that differed to those from the component tasks in Session 16 and the acquired skills have been transferred between task situations. The results showed further that this transfer requires more than eight sessions of practice in the current protocol of hybrid practice.

#### **DISCUSSION**

The present study investigated whether hybrid-practice-related task coordination skills are independent from the specific

characteristics of the practiced component tasks and are thus transferable in a well-controllable practice and transfer context. In particular, transferable skills were shown in the data of the longer auditory task, but not for the data of the shorter visual task of the present task design when both component tasks were changed between practice and transfer. This data is in line with and extents the findings of Liepelt et al. (2011) as well as Strobach et al. (2015b) that provided evidence of skill transfer to dual tasks with only one changed task. These prior findings did not rule out that improved dual-task coordination skills may require constant features between practice and transfer, such as at least one nonchanged component task. The present dual-task transfer test (Session 16) points to a hybrid-practice advantage with changed characteristics in two tasks. Furthermore, our data provide hints for the dose-dependency of transferable task coordination skills, since there is no hybrid-practice advantage after eight sessions when compared with the new single-task group. The hybridpractice advantage in dual tasks emerged only after a doubling of the practice amount.

In general, our findings suggest that the automatization of the combined component tasks (e.g., Ahissar et al., 2001; Ruthruff et al., 2006; Maquestiaux et al., 2008; Strobach et al., 2013; Strobach and Schubert, 2017) is complemented by the acquisition of task coordination skills. Both mechanisms, i.e., task automatization and improvement of task coordination contribute to the practice-related optimization of dual-task processing (Hirst et al., 1980; Kramer et al., 1995). The present data suggest that task automatization has played a rather minor role in the present dual-task context since the component tasks of the post-test (i.e., Session 16) received a small dose of repetitions during prior sessions. Note that the component tasks of the post-test Session 16 were repeated only in Sessions 1, 2, and 8. In all other sessions, we changed the stimuli and stimulus-response mapping rules, which precluded a repeated learning of specific stimulusresponse episodes, which, however, would be needed to enable task automatization (Ruthruff et al., 2006). Moreover, we found large transfer effects in the final Session 16, which was preceded by permanently changing component task situations especially from Session 8 and, partially, also during the Sessions 1-8.

One alternative explanation might be that hybrid practice serves to integrate two tasks more efficiently, to the point of combining them into one single 'super task' (Hazeltine et al., 2002; Ruthruff et al., 2006). According to this super task explanation, one might assume that two separate responseselections processes were performed at the beginning of practice, one response-selection in each component task, while the extensive hybrid practice might have led to the integration of two response-selection processes into one single selection process of a combined task. The processing of only one selection process, instead of two, would reduce dual-task RTs. In fact, the situation of separate practice of two tasks during singletask practice would have prevented integration of both selection processes and would thus prolong RTs in the dual-task situation. However, the integrated selection of two responses after hybrid practice should require that specific pairs of component tasks should be presented constantly throughout the training and that their specific combination should remain constant even in the

post-test session; otherwise in case of permanently changing component tasks, including stimuli and stimulus-response rules, an integrated response-selection process could not emerge and could not transfer from one session to the next; the latter is prevented if the task rules have changed from session n-1 to n, which was precisely the case in the current hybrid training regimen (Hazeltine et al., 2002; Ruthruff et al., 2006). Because we found transfer of skills between changing task situations as a result of hybrid dual-task training, the observed practice-related improvement of dual-task performance cannot be explained by the assumption that both tasks were integrated into one supertask representation.

But how do task coordination skills acquired by participants improve dual-task performance exactly? As illustrated in Figures 1A,B, we assume that the present findings favor a shortened switching operation as a potential realization of improved skills of task coordination (Liepelt et al., 2011; Strobach et al., 2014). A shortened switching operation may be located at the end of the central response-selection stage in the shorter task and before the start of this stage in a longer task (Lien et al., 2003; Band and van Nes, 2006); thus, this shortened operation is particularly suited to explain the exclusive hybrid-practice advantage in the longer (auditory) task and the lacking advantage in the shorter (visual) task. Such a location of the switching operation would be in accordance with the assumption that training may lead to an optimized bottleneck processing being it a structural or strategic in nature (Pashler, 1994; Meyer and Kieras, 1997). A shortened switching operation may relate to a more efficient release (for example, by inhibition) of task information from the shorter task (that turns to an irrelevant task after the switch in a current trial) as well as the activation and instantiation of the response mapping rules of the longer task (De Jong, 1995). Due to its particular locus at the end of central processing in task 1, the shortening of a switching operation after hybrid practice would influence dual-task RTs in the longer auditory task, whereas there should be no (or only a minimal) effect on the shorter visual task of the present dual-task situation. These assumptions may explain the observed processing advantage in the current dual-task situation after hybrid practice.

Additionally, we assume that the proposed mechanism is generalizable in the following way: the shortening of a switching operation after hybrid practice would also influence dual-task RTs in any longer task (i.e., the task with the second response), while there should be no (or only a minimal) effect on any shorter task (i.e., the task with a first response); this generalization is based on the assumption that the order of motor responses is equivalent to the order of the tasks' response-selection stages (Ruthruff et al.,

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Band, G. P. H., and van Nes, F. T. (2006). Reconfiguration and the bottleneck: Does task switching affect the refractory-period effect? 2006). In that case, a hybrid practice effect might lead especially to an earlier start of a task 2 response after the switch and the occurrence of this dual-task training effect should be independent on the specific stimulus and response-selection characteristics of task 2 and task 1 as long as the order of a shorter and a longer task is preserved throughout the training (Strobach et al., 2014). While the current experiment provided evidence for this assumption for the combination of a certain order of a shorter visual motor and an auditory verbal task, other studies may test whether other task combinations would allow for the occurrence of a hybrid dual-task practice advantage located at the longer task (or task 2) of a dual-task situation.

In sum, we demonstrated that task coordination skills improving dual-task performance with practice, are (1) acquired in dual-task situations, (2) transferable, and (3) dose-dependent. Future studies may specify this type of skill acquisition (Taatgen, 2013) and locate its impact in the dual-task processing architecture (Meyer and Kieras, 1997; Schubert, 2008; Strobach et al., 2014).

#### **ETHICS STATEMENT**

Approval by the local ethics committee was obtained before commencement of the study, which was conducted in strict accordance with the local ethics policies of the Humboldt University Berlin, Germany.

#### **AUTHOR CONTRIBUTIONS**

ToS, RL, SK, and TiS were involved in every step of this research project.

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# Walking-Related Dual-Task Interference in Early-to-Middle-Stage **Huntington's Disease: An Auditory Event Related Potential Study**

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Objective: To compare interference between walking and a simple P3 auditory odd-ball paradigm in patients with Huntington's disease (HD) and age- and sex-matched controls.

Methods: Twenty-four early-to-middle-stage HD patients and 14 age- and sex-matched healthy volunteers were examined. EEG-EMG recordings were obtained from 21 scalp electrodes and eight bipolar derivations from the legs. Principal component analysis was used to obtain artifact-free recordings. The stimulation paradigm consisted of 50 rare and 150 frequent stimuli and was performed in two conditions: standing and walking along a 10 by 5 m path. P3 wave amplitude and latency and EEG and EMG spectral values were compared by group and experimental condition and correlated with clinical features of HD.

Results: P3 amplitude increased during walking in both HD patients and controls. This effect was inversely correlated with motor impairment in HD patients, who showed a beta-band power increase over the parieto-occipital regions in the walking condition during the P3 task. Walking speed and counting of rare stimuli were not compromised by concurrence of motor and cognitive demands.

Conclusion: Our results showed that walking increased P3 amplitude in an auditory task, in both HD patients and controls. Concurrent cognitive and motor stimulation could be used for rehabilitative purposes as a means of enhancing activation of cortical compensatory reserves, counteracting potential negative interference and promoting the integration of neuronal circuits serving different functions.

Keywords: dual task, acoustic paradigm, P3, walking, Huntington's disease

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#### INTRODUCTION

Gait disorders are very common among elderly people and people with neurological disorders, causing 17% of all reported falls (Rubenstein, 2006; Axer et al., 2010). The cognitive contribution to gait has been recognized as a cause of postural instability and risk of falling in people showing normal aging and in people with neurodegenerative diseases. This has led to an increase in

research into neural activation during walking, using a variety of techniques including near infrared spectroscopy positron emission tomography (PET), (NIRS), electroencephalography (EEG) (Hamacher et al., 2015). Evaluation of how motor performance is affected by an additional cognitive load has also been used to assess risk of falling in healthy young and old subjects and patients with motor and cognitive impairments (Al-Yahya et al., 2011). The presence of cognitive engagement during gait refers to performance in multiple tasks, with temporal overlap of simultaneous executive functions. It is well-documented that impairment in dual-task (motor-cognitive) performance characterizes neurodegenerative diseases, including Parkinson's disease (PD) (O'Shea et al., 2002), Alzheimer's disease (Camicioli et al., 1997), and multiple sclerosis (Wajda et al., 2013). Although the functions of the musculoskeletal and biomechanical systems during gait are well-known (Kirtley, 2006; Perry and Burnfield, 2010), an understanding of the neuronal processes underlying stable gait is still lacking (Segev-Jacubovski et al., 2011). The dearth of data on cognitive processes during walking is probably due to the difficulty of assessing neuronal functions during the course of the movement. Changes to the spectral components of EEG rhythms in the alpha and beta ranges reflect activation of the motor system during walking (Jasper and Penfield, 1949; Pfurtscheller and Berghold, 1989; Pfurtscheller and Lopes da Silva, 1999; Androulidakis et al., 2007; Zhang et al., 2008; Pogosyan et al., 2009; Joundi et al., 2012; Solis-Escalante et al., 2012; Hamacher et al., 2015), which need to be assessed to understand the interference induced by cognitive engagement. However, EEG signals are susceptible to physiological and non-physiological artifacts, including motion artifacts, that can compromise the decoding of gait and the separation of neural signals related to bipedal locomotion. The EEG activity related to walking may be separated from physiological and non-physiological artifacts, including motion artifacts, using automatic recognition methods (Nathan and Contreras-Vidal, 2016).

In addition, the impact of cognitive interference on gait efficiency can be investigated by recording brain activity related to the cognitive task, as described in previous studies (De Sanctis et al., 2014).

Huntington's Disease (HD) is an autosomal dominant illness characterized by motor and cognitive impairments and psychiatric disturbances. The HD motor impairment is complex and includes akinesia, bradykinesia, and a progressive loss of coordination that affects functional ability (Van Vugt et al., 2004). A general impairment in motor planning cause difficulties of executive functioning, which may better emerge during multitasking experimental paradigms. Moreover, individuals with HD commonly experience falls (Busse et al., 2009), which may partly be the consequence of the inability to perform multiple executing functions, as walking during a contemporary cognitive task.

Recent studies showed that gait speed during a motorcognitive dual task (walking whilst counting backwards) was correlated with United Huntington's Disease Rating Scale Total Motor Score (UHDRSM) (Huntington Study Group, 1996) and performance on a cognitive test (Delval et al., 2008; Fritz et al.,

2016). As HD is a complex disorder in which the cognitive and motor symptoms are inter-related, we aimed to compare reciprocal interference between walking and a simple P3 oddball acoustic paradigm. Considering that the complexity of cortical engagement in walking activity may be described with the modification of EEG spectral components in alpha and beta ranges, the study aimed to evaluate the EEG and EMG correlates of this multitasking procedure in HD patients compared to age and sex matched controls. The study specifically intended to assess if (1) the P3 features would be modified differently by walking in HD patients and controls. (2) the changes of motor activity during walking due to cognitive engagement differed between HD patients and controls (3) the P3 task would induce different effects on EEG activities related to walking in HD patients and controls.

#### **METHODS**

The study was approved by Bari Policlinico General Hospital Ethical Committee, and all subjects provided written, informed consent to participation and publication of data that could identify them under a code. Preliminary results from healthy subjects were presented at the 6th IEEE International Workshop on Advances in Sensors and Interfaces, IWASI 2015 (de Tommaso et al., 2015). The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans (World Medical Association, 2013).

# Subjects

Twenty-four HD patients being followed at Apulian regional referral center for HD were enrolled in the study. Fourteen age- and sex-matched healthy volunteers were also examined. Demographic and clinical data for the patient group are reported in Table 1. Exclusion criteria were evidence of general medical or other neurological and psychiatric diseases and any kind of auditory impairment. Decisions about whether the exclusion criteria were met were based on a detailed interview, medical history, and objective general and neurological examinations. Patients who were able to walk along a short course without support were recruited. Two patients were excluded as they showed a marked tendency to fall and total incapacity to walk unaided during the task.

Patients underwent the motor section of Unified Huntington's Disease Rating Scales, (UHDRS) (Huntington Study Group, 1996) and the Mini Mental State Examination (Folstein et al., 1975). The distribution of age and sex was similar in the patient and control groups (Table 1).

#### Recording

EEG—EMG recordings were obtained using MICROMED EEG apparatus Micromed Brain Quick, Mogliano Veneto, Italy). EEGs were recorded using a prewired head cap with 21 Ag-AgCl surface electrodes; further electrodes above the right and left eyebrows that were referenced to the nasion were used for the electro-oculogram (EOG). A 0.1-100 Hz band-pass filter with a 50 Hz digital filter was applied during recording of EEG

TABLE 1 | Demographic and clinical characteristics of HD patients and controls.

Drugs	Neuroleptics, SSRI	None	Neuroleptics, SSRI	None	Atypical neuroleptics	Neuroleptics, SSRI	None	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI	None	None	Neuroleptics, SSRI	Neuroleptics, SSRI	Neuroleptics, SSRI, tricyclic antidepressants	None	Neuroleptics, SSRI
Mini mental	27	30	27	27	25	27	23	18	27	56	20	19	23	25	25	30	22	28	27	23	23
Posture	4	0	-	-	0	-	0	-	Ø	-	Ø	-	-	N	0	-	C/	-	7	0	-
Tandem walking	4	0	-	-	0	ო	2	Ø	Ø	Ø	ო	4	-	N	2	-	-	-	<del>-</del>	0	m
Walking	4	0	-	0	0	N	-	CV	0	0	ო	0	-	-	-	0	-	-	-	0	0
Dystonia lower limb	0	0	0	0	0	0	0	0	0	Ø	0	9	0	-	0	0	ო	2	0	0	0
Total dystonia	ო	0	0	-	-	ო	-	Ø	ო	∞	-	Ø	N	4	-	-	4	9	<del>-</del>	0	-
Bradikinesia	4	0	-	0	0	4	2	0	ო	0	က	67	-	0	C/	0	-	2	-	0	2
Chorea lower limbs	4	0	N	2	0	Ø	2	N	4	N	N	-	4	N	2	7	N	N	0	0	4
Total	17	2	_	2	ιO	7	7	∞	4	<b>o</b>	_	4	10	_	7	D	7	9	∞	0	12
UHDRSM	88	2	25	15	16	55	36	44	58	51	55	49	44	48	35	15	59	42	59	Ю	47
Sex	Σ	ш	Σ	Ш	Σ	Σ	L	ш	Σ	Σ	Σ	ш	ш	Σ	ш	Ш	ш	Σ	ட	Σ	Σ
Age	35	32	29	59	45	94	42	20	22	23	69	38	47	52	42	41	54	35	56	30	43
Patients CAG Duration (years)	ω	0.5	13	2	1.7	ιO	-	56	∞	9	17	ω	ω	9	-	2	9.8	ω	<del>-</del>	0.7	_
CAG	51	47	14	23	42	41	45	41	14	46	42	49	44	42	45	45	14	48	40	47	47
Patients	-	2	ო	4	2	9	7	ω	0	10	=======================================	12	13	14	15	16	17	18	19	20	21

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Patients	CAG	Patients CAG Duration (years)	Age	Sex	UHDRSM	Total	Chorea Iower Iimbs	Bradikinesia Total dystonia	Total dystonia	Dystonia lower limb	Walking	Walking Tandem walking	Posture	Mini mental	Drugs
22	42	rð.	26	ш	65	13	4	2	0	4	-	2	-	23	Neuroleptics, SSRI
23	40	2.7	29	Ш	25	က	2	-	4	0	-	-	-	23	None
24		∞	59	Σ	30	∞	0	2	4	-	-	0	-	29	Neuroleptics, SSRI
HD patients Controls			M = 48.13, $SD = 11.53$ $M = 48.8$ , $SD = 14.13$ , $ANOVA$ : $F = 1.23$ , n.s.	12 M, 12 F 7 M, 7 F, $\chi^2 = 1.21$ , n.s.	M = 37.71, SD = 20.21	M = 7.4, $SD = 3.8$	M=2.21, SD=1.12	M = 1.6, $SD = 1.1$	M = 2.8, $SD = 2.7$	M = 0.79, $SD = 1.5$	M = 1.25, SD = 0.98	M = 2.8, $M = 0.79$ , $M = 1.25$ , $M = 1.7$ , $M = 1.12$ , $M = 24.87$ , $SD = 2.7$ $SD = 1.5$ $SD = 0.98$ $SD = 1.12$ $SD = 1.89$ $SD = 3.24$	M = 1.12, SD = 1.89	M = 24.87, SD = 3.24	

SSRI: Total Unitied Huntington's Disease Motor Rating Scale (UHDRSM) score and some item scores are reported. The tandem walking is a gair where the toes of the back foot touch the heel of the front foot at each step.

data. Further derivations were used to record electromyography (EMG) signals from the right and left anterior tibialis and right and left lateral gastrocnemius, using superficial Ag-AgCl electrodes fixed by collodion. The ground electrode was positioned over the cervical zone. The amplifier box was carried in a backpack and electrode cables were carefully fixed to the legs. All subjects wore a wrist pedometer.

# P3 Task

The auditory task was controlled via the Brain Quick Micromed program. Two types of acoustic stimuli (50 rare stimuli; 150 frequent stimuli) were delivered at random intervals (1-3 s). The stimuli consisted of pure tones of 70 dBL SPL intensity with a duration of 100 ms and a rise and fall time of 10 ms. The frequency of the rare stimulus was 1,000 Hz and the frequency of the frequent stimulus was 250 Hz. The sounds were delivered freely in the experimental environment using two loudspeakers; subjects did not wear acoustic cups and were asked to attend to and count the rare stimuli. The output variable was total number of errors (omissions and false hits).

# **Experimental Procedure**

The experiment was carried out in a quiet and soundless room in which a 10 m by 5 m path had been marked out. Subjects were asked to walk up and down this path, walking as naturally as possible, whilst wearing the electrodes and carrying the backpack on their shoulders. Data were recorded whilst subjects were standing for 5 min (C1); walking for 5 min (C2); standing for 5 min whilst performing the P3 odd-ball task (C3); walking for 5 min whilst performing the P3 odd-ball task (C4). The sequence of the four experimental conditions was randomized across patients and controls. All the subjects were tested during the morning. Walking speed was evaluated through the pedometer.

# **EEG-EMG Analysis**

The ASA software, vers. 4.7.3.1 by ANT software (http:// www.ant-neuro.com/products/asa) was used for EEG and EMG analysis. Both EEG and EMG signals were sampled at 256 Hz. A multi-step artifact removal procedure was applied to ongoing EEG in order to generate reliable EEG signals and eventrelated potentials for analysis. After visual inspection of EEG recordings, the frequency, and amplitude of electrode oscillations were characterized on a per subject basis. An automatic artifact recognition and removing was previously performed for the slow oscillations present on the EOG and EMG channels, exceeding 150  $\mu$ V amplitude. The remaining EEG recording was corrected using a principal component analysis (PCA) method that models the brain signal and artifact subspaces (Ille et al., 2002), according to ASA software. PCA is a reliable method of extracting EEG components based on temporal and spatial features. This method separates brain signals from artifacts, removing the artifacts without significantly distorting the EEG. It is well-applied to extract event-related potentials (Dien et al., 2007), and may also support the recognition and consequent removal of well-defined artifact activities. (ter Braack et al., 2013). The artifact correction method, implemented in ASA software, uses two criteria to determine which part of the data is considered signal (data subspace). The first criterion specifies the highest permitted amplitude of the brain signal and the second criterion specifies the highest permitted correlation between brain signal and artifact topography. PCA is then used to determine the topographies of the artifact-free signals and the artifacts. Separation was achieved by means of data intervals with a clear artifact activity. We implemented PCA separately for the different types of artifact, which were marked for the following analysis: (1) repetitive electrode oscillations during walking (activity in the 0.5-1 Hz range present on the 21 scalp electrodes; (2) eye movements in the 0.5-2 Hz frequency range, with prevalent amplitude over the frontal (Fp1,Fpz,Fp2) electrodes; (3) rarer low frequency, non-repetitive electrode oscillations in HD patients due to choreic movements, which persisted after automatic rejection of activity exceeding 150 µV. The time basis considered was the longest duration we have marked, the amplitude threshold was 100 µV, the maximal correlation with artifact subspace was settled at the default value of 50%, the minimal variance with the data subspace at the default value of 10%. A similar PCA was applied to EMG recordings to subtract the main slow artifacts. We took into consideration the limited reliability of dynamic spectral analysis (Farina, 2006) and simply considered the total spectral power of EMG activity in the walking and walking+P3 conditions, filtered in the 10-90 Hz frequency range and normalized by subtracting standing condition values on a per subject basis.

The modifications of spectral components of ongoing EEG activity, were evaluated by filtering the EEG in the 7-12 and 13-30 Hz frequency ranges (corresponding to alpha-mu and beta rhythms). In fact these frequencies are specifically modified during walking, and could describe the interference due to a contemporary cognitive task (Hamacher et al., 2015).

For the cognitive task, we averaged at least 30 artifactfree EEG recordings corresponding to presentation of rare and frequent stimuli and extracted the P3 component, considering 100 ms as prestimulus and 900 ms as poststimulus times with a baseline-correction for dc (direct current) offset subtraction with 0.5 s duration, according to ASA software Version 4.3.1. For P3 analysis, the EEG was filtered in the 0.1-70 Hz frequency range. We performed a semiautomatic peak detection with the maximum area of the P3 wave, which considered at least 50% amplitude prevalence of the positive wave in the time range 200-500 ms obtained by the rare and frequent stimuli. The results of semiautomatic analysis were validated by visual inspection of the data.

# Statistical Analysis

We assessed the normality of the distribution of data using the Kruskal-Wallis test. A preliminary MANOVA analysis with EEG channels as variables and condition rare-frequent stimuli as factors, was employed separately in HD and control groups to ensure the reliability of P3 wave. P3 wave amplitude, P3 latency and log-transformed EEG and EMG spectral values were evaluated by multivariate analysis of variance (MANOVA) (complete factorial model, sum of squares type III) with EEG and EMG channels as variables. The main MANOVA factors were condition (for EEG bands: standing for 5 min -C1- vs.

walking for 5 min -C2- vs. standing for 5 min whilst performing the P3 odd-ball task -C3- vs. walking for 5 min whilst performing the P3 odd-ball task -C4-; for P3 amplitude: standing for 5 min whilst performing the P3 odd-ball task -C3- vs. walking for 5 min whilst performing the P3 odd ball task; for normalized EMG spectral components: walking for 5 min -C2- vs. walking for 5 min whilst performing the P3 odd-ball task -C4-) and group (HD vs. control). Considering that age had a consistent variability within groups, we included it in the MANOVA as a control variable. Separate post-hoc Bonferroni tests (for EEG bands comparing C1 vs. C2 vs. C3 vs. C4) and paired-sample t-tests with Bonferroni correction (for P3 amplitude, P3 latency, C3 vs. C4, for normalized EMG spectral component; C2 vs. C4) were carried out for each group using SPSS v. 21.

We also employed a linear regression test with the main clinical features of HD as independent factors and P3 amplitude and EMG spectral components as dependent variables, using the condition walking vs. standing (C3-C4) and walking without and during the P3 (C2 and C4), as selection variables.

The main P3 topography was represented using Scalp Maps, provided by ASA software (4.7.3 software version, by ANT software http://www.ant-neuro.com/products/asa). The detailed analysis, including spectral data and amplitudes, as well as the detailed statistical analysis is presented in a supplementary section.

#### RESULTS

# Task Performance

All subjects performed the walking task. The control group's mean walking speed was  $1.9 \, \text{m/s} \pm 0.23$  in the single-task condition C2 and 1.88 m/s  $\pm$  0.24 in the dual-task condition C4 (walking+P3 task). The patient group's mean walking speed was 1.21 m/s  $\pm$  0.44 in the single-task condition C2 and 1.19 m/s  $\pm$ 0.38 in the dual-task condition C4. ANOVA showed an effect of diagnosis (F = 7.37, p < 0.01), but there was no effect of condition (F = 1.23, n.s.) and no condition x diagnosis interaction (F =1.45, n.s.). For the control group the target stimuli errors rate was  $2.3 \pm 0.5$  in the single-task condition C3 and  $2.4 \pm 0.8$  in the dualtask condition C4 (walking+P3). For the patient group it was  $3.1 \pm 0.9$  in the single-task condition C3 and  $3.2 \pm 0.8$  in the dualtask condition C4. ANOVA indicated that there was no effect of diagnosis or condition on performance of the P3 task.

#### P3 Amplitude

The preliminary MANOVA analysis assessed a significant amplitude prevalence of the response in the 200-500 ms time interval to the rare stimulus compared to the frequent one (controls F-value-Roy's largest root- 2.99 hypothesis DF 21, DF 1; error DF 6 p < 0.01; HD F 2.48, hypothesis DF 21, DF 1, error DF 26 p < 0.01 in standing condition; controls F 3.01 p < 0.01; HD 2.55 p < 0.01 in walking condition). The P3 amplitude was similar in both groups, and condition (walking C4 vs. standing C3) had a significant effect in both groups (Table 2, Table S1), though this was more evident in controls (Figures 1, 2, Tables S1, S2).

TABLE 2 | MANOVA analysis (Roy's largest root) for alpha and beta rhythm, muscular activity. P3 amplitude, and latency with electrodes (21 for alpha and beta activity and P3 amplitude, 4 for EMG activity) as variables and diagnosis controls vs. HD and conditions walking vs standing vs. P3 walking vs. P3 standing as factors.

	F	Hypothesis DF	DF	Error DF	Sig.
P300 AMPLITUDE					
Diagnosis	0.0714	21	1	52	n.s
Condition	2.5	21	1	52	0.01
${\sf Diagnosis} \times {\sf Condition}$	2.1	21	1	52	0.04
ALPHA RHYTHM					
Diagnosis	4.29	21	1	292	0.0001
Condition	4.97	21	3	290	0.0001
${\it Diagnosis} \times {\it Condition}$	2.29	21	3	290	0.008
BETA RHYTHM					
Diagnosis	3.38	21	1	292	0.0001
Condition	3.83	21	3	290	0.0001
${\sf Diagnosis} \times {\sf Condition}$	1.72	21	3	290	0.042
10-90 Hz MUSCLE AC	CTIVITY (N	NORMALIZED)			
Diagnosis	9.75	4	1	79	0.0001
Condition	1.33	4	1	79	n.s.
Diagnosis × Condition	0.73	4	1	79	n.s.

# P3 Latency

P3 latency measured at the Pz channel was similar in the two groups. Both groups showed a non-significant decrease in walking conditions C4 (Figure 3, Table 3).

# **EMG/EEG Activity Power Spectra**

Spectral analysis of muscle activity during walking C2 and walking+P3 conditions C4 was standardized by subtracting standing condition activity on a per subject basis. There was a main effect of diagnosis but no effect of condition and no diagnosis × condition interaction (Figures 4, 5, Table 3).

In HD patients descriptive data suggested that muscle recruitment during walking was further reduced during the dualtask condition (P3+walking, C4) (Figures 5, 6), but Student's ttests showed that the reduction was only significant for the right anterior tibial muscle. (Figures 4, 5).

#### Alpha Activity

The MANOVA model showed that there were main effects of diagnosis and condition on alpha activity as well as a diagnosis × condition interaction (Table 2). The cognitive task did not cause a change in alpha activity in the standing C3 or walking conditions C4. In controls alpha activity was greater in the walking C2 and P3+walking conditions C4 compared to the standing C1 and P3+standing C3 conditions respectively, over several electrodes, in particular the frontal and temporo-occipital electrodes (Figure 6, Table 2, Table S3). In HD patients the alpha activity in standing C1 and P3 standing C3 conditions were quite similar to normal values, while in the course of walking and P3 walking (C2, C4) there was only a slight and not significant increase of alpha power. (Figure 6).

#### **Beta Activity**

MANOVA also showed effects of diagnosis and condition on beta activity, as well as a diagnosis × condition interaction (Figure 5, Table 2, Table S4,). In both HD patients and controls, the beta power did not change significantly in the standing C1 vs. P3 standing C3 and walking C2 vs. P3 walking C4 conditions (Figure 6). In controls the Bonferroni test showed a significant increase of beta power in the walking C2 and P3 walking C4 vs. standing C1 and P3 standing C3 conditions interesting one frontal electrode and the bilateral occipital derivations (Figure 6). In HD patients, the beta rhythm was increased in walking P3 task C4 over the temporo-parietal electrodes as compared to the standing C1 and P3 standing C3 conditions. (Figure 6, Table S4).

# **Linear Regression Analysis**

In HD patients P3 amplitude was negatively correlated with UHDRSM, bradykinesia, and walking scores in the walking C4 condition, but not in the standing C3 condition (Figure 7, Table 4). During the walking task C2 recruitment of the right gastrocnemius and anterior tibial muscles was negatively correlated with illness duration (Table S5). The muscle recruitment of the right gastrocnemius and anterior tibial muscles during the walking task C2, was inversely correlated with illness duration, the muscle recruitment of the right gastrocnemius was also negatively correlated with bradykinesia, walking, and tandem walking items. (Table S5). This correlation was absent when patients performed the P3 task in the C4 condition(Figure 8, Table S5).

ANOVA indicated that in the patient group neuroleptic treatment did not affect any of the outcome variables-P3 amplitude, P3 latency, alpha, and beta activity and muscle recruitment.

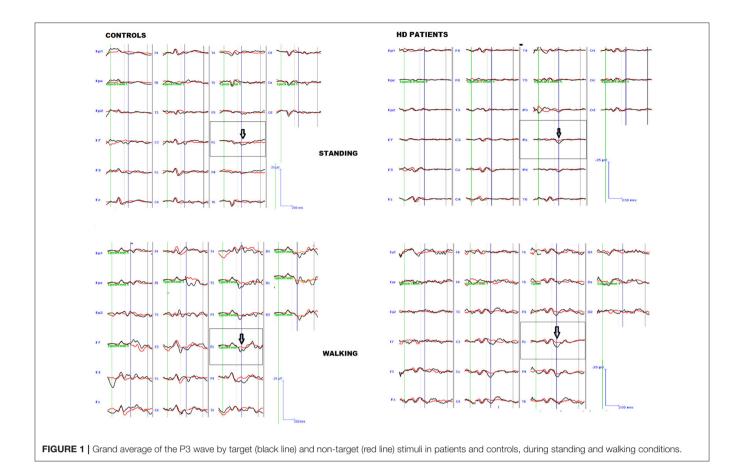
# DISCUSSION

The results of this study could indicate that the P3 features were not substantially dissimilar between patients and controls, and that its amplitude appeared enlarged during walking in both groups, though this phenomenon was less evident in patients. The cognitive engagement did not cause a deterioration of motor performance in controls and patients, though in the latter group it was associated with a slight reduction of muscle recruitment. The EEG spectral correlates of walking in the alpha and beta frequency ranges, were generally increased during movement in control subjects and not significantly modified by concurrent P3 task. In HD patients this effect was evident in regard to the beta rhythm.

The discussion is organized as follows: comments to the main results, followed by the limitations of the study and general conclusions.

# P3 Features in Basal Conditions and **Walking Conditions**

P3 amplitude increased during walking in both HD patients and controls. In the basal conditions there were no group differences in P3 amplitude or latency. All the patients included in this



study were capable of independent walking and had normal or slightly reduced MMSE scores, i.e., had mild symptoms of HD. The nature and extent of P3 abnormalities vary between HD cohorts. In an earlier study of early-stage HD patients and atrisk presymptomatic subjects we found that the P3 latencies of the majority of HD patients and all presymptomatic gene carriers were within the normal range (de Tommaso et al., 2003b). More recent studies have shown that the latency of the P3 wave is increased at several stages of HD (Beste et al., 2010; Hart et al., 2012, 2015). These apparent discrepancies may be due to differences in the experimental procedures used in the P3 task and the different clinical conditions of the patient samples. In our procedure, subjects were required to detect an acoustic target but did not use a motor action to indicate target detection, while most of the studies which have found abnormal P3 latencies have used go/no-go paradigms, that could reveal deficits in pre-motor inhibition and motor preparation (Beste et al., 2010; Hart et al., 2012, 2015). A clear increase in P3 latency was observed in a visual task, with a delay affecting the early visual components; this result suggests that HD patients may have a particular problem with visual stimulus processing (Muente et al., 1997). Compensatory mechanisms for coping with specific cognitive deficits and paradoxical enhancement of cognitive functions not specifically related to motor performances have also been described in HD (Beste et al., 2014; Hart et al., 2015). Our failure to find P3 abnormalities in our HD series may be due to our use of

a purely auditory task that does not require a motor response and our recruitment of patients with only slight or moderate cognitive impairment. The percent rate of errors in counting the target stimuli was non-significantly higher in HD patients, confirming that the cognitive process of stimulus recognition is normal in the early and middle stages of the disease when motor preparation for a go or no-go response is not required.

Walking produced a clear increase in P3 amplitude in both groups. This is a novel finding as few studies have evaluated event-related brain activity with dual-task paradigms. In P3 studies on healthy volunteers comparing sitting in a quiet room with walking in environments with substantial ambient noise, the response to target stimuli seemed reduced during outdoor movement, an effect partly attributable to the environmental distractors as busy streets and traffic (Debener et al., 2012). A previous study that evaluated the effect of treadmill walking on the performance of a visual P3 go/no-go task in healthy subjects, found a reduction in the amplitude of the N2-P3 inter-peak amplitude and an increase in its latency in the no-go target condition (De Sanctis et al., 2014). In that study the P3 task involved a motor response and hence potential recalibration of the cortical resources engaged in the inhibitory motor task to optimize performance in dualtask contexts (De Sanctis et al., 2014). The same authors also found an increase in amplitude of the P3 peak over the central sites, indicating that even in this dual-task context

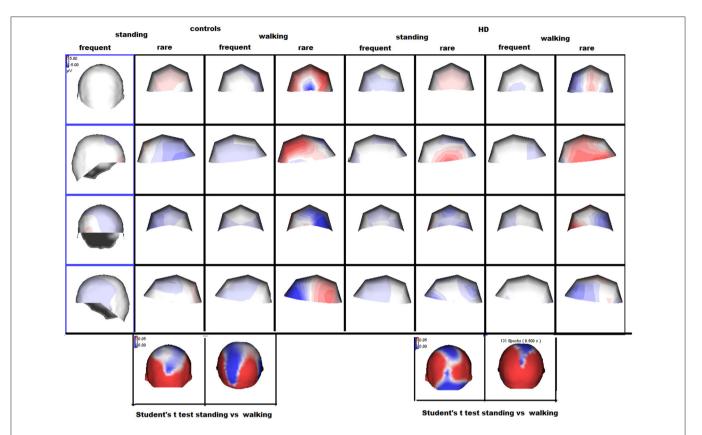


FIGURE 2 | Scalp maps of the P3 wave by rare and frequent stimuli are reported. The amplitude maps at the bottom of the figure represent the results of separate Student's t-tests for each group, where the color scale indicates the p-values. Significant results are shown in white and blue.

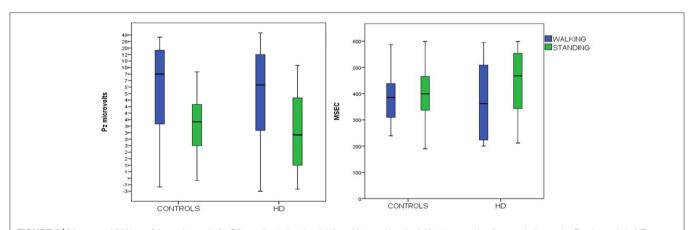


FIGURE 3 | Means and 95% confidence intervals for P3 amplitude (on the right) and latency (on the left) to target stimuli, recorded over the Pz channels in HD patients and controls, during standing and walking conditions.

the P3-related processing was improved when subjects were walking.

Our task was different as it was based on acoustic discrimination of the rare stimulus, with no involvement of cortical resources competing with the walking task. With our task the act of walking seemed to increase rather than reduce cortical involvement in the acoustic discrimination task, even in HD patients. The P3 showed a typical amplitude distribution over

the central-parietal regions across the midline in both groups, although the increase was more topographically restricted in HD patients. Previous dual-task studies have reported that the majority of HD subjects experienced interference between gait and cognitive performance, such that under dual-task conditions cognitive performance decreased when gait speed increased (Fritz et al., 2016). Accordingly, in people with neurologic disease, the attention demanding exercise of walking affect the

TABLE 3 | ANOVA analysis.

P3 latency	F	DF	Sig.	Error
Diagnosis	2.52	1	n.s	
Condition	0.55	1	n.s.	
Diagnosis × Condition	0.44'	1	n.s.	
				72

P3 latency computed over the Pz electrode as factor.

cognitive resources (Yogev-Seligmann et al., 2008), requiring greater cortical activation. In the present study we employed a standard P3 auditory task to record reliable event related responses, avoiding to use the typical alphabetic paradigm (Fritz et al., 2016). This type of cognitive test did not change walking speed in controls during the P3 task and only slightly reduced it in HD patients, suggesting that the interference with walking is related to the type of cognitive engagement. However, in HD patients the P3 task caused a reduction in muscle recruitment, suggesting a slight influence on motor performance. Dynamic exercise can improve cognitive function and increase blood flow within the prefrontal cortex (Endo et al., 2013). Extensive cortical activation including the supplementary motor area (SMA), frontal gyrus, insula, and cingulate cortex has been observed in walking (Hamacher et al., 2015). The SMA plays important, albeit different, roles in various cognitive domains including action, temporal, and spatial processing, numerical cognition, music, and language processing and working memory (Cona and Semenza, 2016). The increase in P3 amplitude observed during walking in both healthy subjects and HD patients suggests that the cortical regions that generate this wave were activated rather than inhibited by the contemporary movement. However, the increased P3 amplitude was not associated with a real cognitive facilitation, i.e., reduced detection latency and better recognition performance, instead it was accompanied by preservation of single-task levels of P3 performance during the dual-task condition. Activity in cortical regions responsible for integrating use of motor and cognitive executive functions may have been responsible for preservation of cognitive ability during walking and this probably accounts for the more extensive cortical activation we observed under dual-task conditions. Further research is needed to determine the extent to which motor activity facilitates the execution of cognitive tasks in HD patients. The hypothesis that motor activity facilitates cognitive processing was derived from studies showing physical exercise retards neurodegeneration in Alzheimer's disease (Okonkwo et al., 2014). Another point worth of deep examination would be the type of cognitive engagement subjected to possible facilitation rather than inhibition during walking, maybe a pure cognitive task not requiring motor action. In HD patients, the motor impairment, measured as UHDRM score, was negatively correlated with P3 amplitude during walking. This may be due to sensory feedback to the cortical regions responsible for motor and cognitive strategies from the body parts involved in walking. Functional magnetic resonance imaging (FMRI) studies have revealed that in PD the motor impairment caused by freezing reduces patients' capacity to recruit specific cortical and subcortical regions within the cognitive control network (Shine et al., 2013). Similarly, HD patients with more severe motor impairment showed reduced activation of cortical regions subtending P3 scalp representation during walking relative to patients with a less severe motor impairment. Increased recruitment of the cortical regions generating the P3 component during walking seems to be dependent upon the motor efficiency of HD patients.

# **EMG Power Spectra and Walking Speed**

The P3 acoustic task did not reduce the ability of motor task execution and walking speed in controls or HD patients, unlike the alphabetic test usually used in dual-task paradigms (Verghese et al., 2002). This suggests that the type of cognitive processing required to perform the acoustic odd-ball task does not have a negative effect on walking performance. Studies in PD patients have shown that rhythmic auditory stimulation improves motor functions and balance (Song et al., 2015). Our P3 task involved random acoustic stimulation that may have enhanced the rhythmicity of walking without competing with walking for attentional resources. Overall muscular recruitment during walking was reduced in HD patients, although the P3 task only had a negative effect on muscle activation at one site, the tibial anterior muscle, with a similar trend in controls. The anterior tibial muscle has a primary role during walking (Montgomery et al., 2016) and this may explain why it was subjected to interference from concurrent performance of the cognitive task. In HD patients motor impairment, as reflected in bradykinesia and deficits in the UHDRSM walking items, was correlated with reduced muscular recruitment. However, this correlation was absent in the dual-task condition, presumably because the attentional demands of the cognitive task caused a further reduction of muscular recruitment. This finding suggests that the acoustic P3 task could in part cause a deterioration of motor performance during walking, also in patients with better motor abilities, although use of compensatory motor strategies may contribute to preserve motor speed.

# **EEG Spectral Analysis- Alpha and Beta** Activity Changes during Walking

Unlike previous studies we did not find a reduction in alpha power in our HD patients in the basal condition but we observed a scarce alpha rhythm modulation in the walking conditions. In the control group there was a clear increase in alpha activity over the frontal and occipital regions in the walking and walking+P3 conditions, but this effect was much smaller in the HD group. Previous studies have reported that a closed-eyes condition reduces alpha power in HD patients (Scott et al., 1972; Bylsma et al., 1994; de Tommaso et al., 2003a; Bellotti et al., 2004; Painold et al., 2010). This finding, together with our results, suggests that in HD patients modulation of the amplitude and synchronization of EEG rhythms in the alpha band may be impaired in several conditions, including eyes closed and active movement. During walking our control group displayed a clear increase in alpha band EEG activity over the frontal regions that probably correlates with activation of the motor cortical network (Hamacher et al., 2015). In high density EEG studies

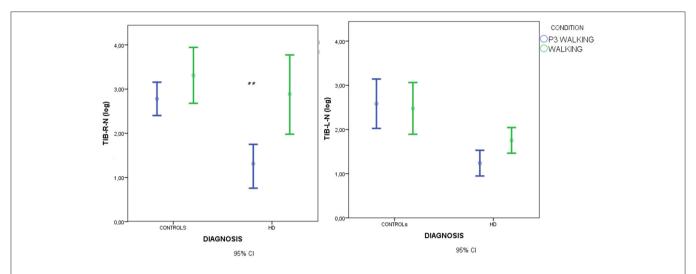


FIGURE 4 | Means and 95% confidence intervals (CI) for the total spectral power of EMG activity, normalized by standing condition values and log-transformed, in the walking and walking +P3 conditions in HD patients and controls. Values from right anterior tibial (TIB-R-N-log) and left anterior tibial (TIB-L-N-log) muscles are reported. Results of separate paired-samples Student's t-tests for each group: \*\*p < 0.01.

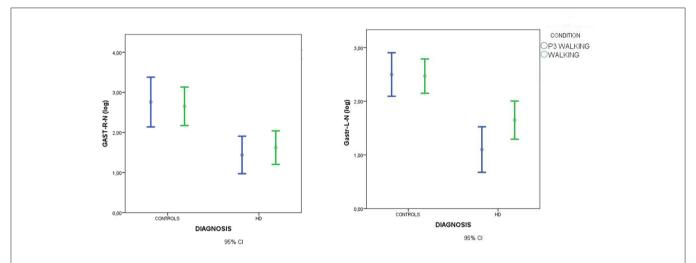


FIGURE 5 | Means and 95% confidence intervals (CI) for total spectral power of EMG activity, normalized by standing condition values and log-transformed, in the walking and walking +P3 conditions in HD patients and controls. Values from right gastrocnemius (GSTR-R-N-log) and left gastrocnemius (GASTR-L-N-log) muscles are reported. Separate paired-samples Student's t-tests for the two groups were not significant.

an alternating synchronization-desynchronization pattern was observed during treadmill walking, accompanied by fluctuating alpha and beta amplitudes during the gait cycle (Gwin et al., 2011; Hamacher et al., 2015). The alternating synchronizationdesynchronization of alpha and beta bands during a single step sequence, may be totally in favor of an increase in EEG power in these frequency ranges across the whole gait cycle (Severens et al., 2012), which would account for the results we obtained in controls when we computed the EEG spectrum components over the entire walking task. In controls, there was a bilateral increase in alpha power over the frontal regions during walking, a finding which is compatible with the notion of cortical sources in prefrontal cortex, as indicated by high density EEG (Gwin et al., 2011). We also observed an increase in alpha power over the occipital electrodes, probably due to activation of the posterior regions involved in the visual exploration of the walking route, or to a diffusion of activity from the posterior parietal sources (Gwin et al., 2011). Severens et al. (2012), demonstrated that there was more beta and gamma band synchronization than alpha synchronization in EEGs recorded during walking, as a consequence of movement-induced artifacts, so our finding of a prevalent alpha band more than beta band increase during walking seems to be reliably attributable to walking-related cortical activation. Moreover, artifacts would be even more expressed in HD patients, who, despite this, showed a smaller increase in alpha band power during walking. In controls the

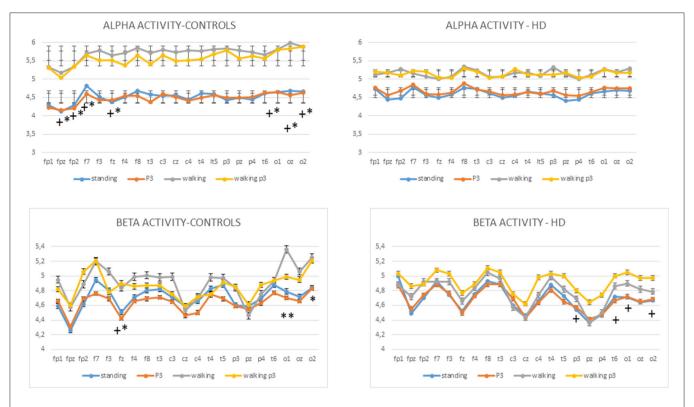


FIGURE 6 | Mean values and standard errors for alpha activity (top) and beta activity (bottom) in controls and HD patients. The results of separate Bonferroni tests for each group are reported, standing vs. walking and standing+P3 vs. walking+P3: \*p < 0.05, \*\*p < 0.01; standing vs. walking+P3 and standing+P3 vs. walking+P3: +p < 0.05

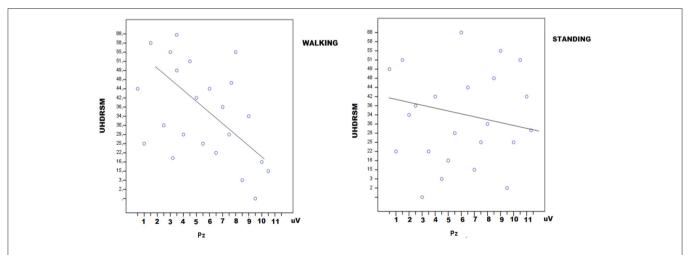


FIGURE 7 | Linear dispersion graph for UHDRSM scores (Unified Huntington's Disease Rating Scale-Motor) and P3 amplitude over the Pz electrode in walking and standing conditions. A negative correlation was present in the walking condition (detailed statistical results are reported in Table 4).

trend in beta activity was similar to the changes in alpha activity, though this effect was limited to few frontal and posterior electrodes. The P3 task did not cause detectable modification of the alpha and beta power representation in either the standing or walking conditions, presumably because the P3 task is mainly associated with activity in the delta and theta bands (Basar-Eroglu

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et al., 1992; Yordanova and Kolev, 1998; Karakaş et al., 2000), while changes in alpha and beta bands are limited to the prestimulus time (De Blasio et al., 2013). Moreover, there is evidence that increased alpha power is generally associated with better cognitive performance, so the EEG activation induced by walking should facilitate cortical recruitment to the odd-ball task

(Ramos-Loyo et al., 2004). In HD patients, the lack of increase in alpha activity during walking may be due to a basic defect in EEG rhythm modulation, rather than to cognitive interference. In HD patients the dual-task condition produced modulation of the beta rhythm over the temporal-parietal-occipital regions. Reports of abnormalities of beta rhythm in HD samples have been inconsistent (de Tommaso et al., 2003a; Painold et al., 2010), suggesting that beta rhythm is slight affected by the basal mechanisms of the disease, and prone to modulation by cognitive and motor tasks. In HD patients the increase in beta band power over the parietal and occipital electrodes appears to reflect visual

TABLE 4 | Linear regression analysis for P3 amplitude on Pz electrode and main clinical features in HD patients UHDRSM.

	DF	F (walking)	Sig	F (standing)	Sig
Linear regression analysis	12	3.648	0.024	1.067	0.466
Single independent variables		t		t	Sig.
		(Walking)		(Standing)	
CAG		1.006	0.338	1.252	0.239
Duration		1.313	0.218	1.715	0.117
UHDRSM		3.442	0.006	0.305	0.767
Chorea		1.799	0.102	0.966	0.357
Chorea lower limb		2.145	0.058	0.331	0.748
Bradikinesia		2.737	0.021	0.116	0.910
Dystonia		1.379	0.198	-1.112	0.292
Diystonia lower limb		1.463	0.174	1.580	0.145
Walking		2.963	0.014	0.290	0.778
Tandem Walking		1.979	0.076	0.445	0.666
Posture		1.231	0.246	1.292	0.225
MMSE		2.121	0.060	-1.415	0.187

Motor section of Unified Huntington's Disease Rating Scale. Statistical significance are outlined in bold.

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perceptual processing during walking, which became evident during the P3 task. This suggests that in HD patients cortical compensatory mechanisms may be used to preserve cognitive performance during motor tasks.

#### STUDY LIMITATIONS

Despite we were able to detect spontaneous and evoked EEG activity even during dynamic condition in patients affected by movement disorders, the study suffers from main methodological flaws, as we employed standard EEG apparatus, which did not allow us to record accelerometer parameters or obtain reliable data on walking performance. In addition, the presence of cable connections made walking more difficult, especially for the HD patients.

Our primary aim was to evaluate the mutual interference between the EEG-EMG correlates of walking and the P3 wave, but the effect of cognitive interference on motor performance would be better investigated using wireless apparatus. Using a real walking route rather than a treadmill task increased the ecological validity of our walking task. Our artifact removal technique appeared to be efficacious for most of the EEG and EMG patterns we investigated, though we decided to limit our event-related potentials analysis to the P3 response to reduce the possibility of confounding results.

Finally, our HD group included patients taking neuroleptic medication. This subgroup appeared to have similar EEG characteristics to the untreated subgroup, but the possibility that there were subtle, drug-induced modifications of EEG rhythms cannot be excluded.

### **CONCLUSIONS**

The main significance of our findings is that in HD patients and controls the cortical activation during P3 task increased during walking, without adversely affect the changes of EEG alpha and

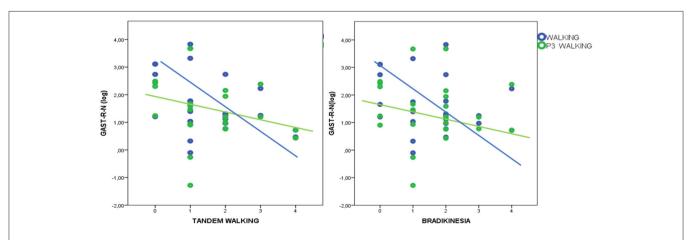


FIGURE 8 | Linear dispersion graph for bradykinesia and tandem walking (Unified Huntington's Disease Rating Scale-Motor items) and right gastrocnemius muscle recruitment (total spectral power of EMG activity, normalized by standing condition values and log-transformed) during walking and walking+P3. A negative correlation was present only in the walking condition (detailed statistical results are reported in Table S5).

beta bands induced by movement. This is in favor of a positive interference between walking and certain modalities of cognitive paradigms, as the general brain activation induced by walking may facilitate the cortical engagement in the P3 task, in the attempt to preserve both gait and cognitive performances. In HD patients the association with the cognitive tests produced only a slight and not relevant deterioration of motor speed and muscle recruitment, but the dual-task condition caused some modulation of EEG beta band activity. These findings suggest that combined cognitive and motor stimulation, in the form of dual-task conditions, could be used for rehabilitative purposes, as a means of enhancing the activation of compensatory cortical reserves and thus counteract potential interference between cognitive and motor processes and promote the integration of neuronal circuits serving different functions.

### **HIGHLIGHTS**

HD patients and controls performed an auditory P3 task whilst

During walking P3 amplitude was higher and EEG rhythms were modulated in HD and controls.

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Cortical activation may promote the integration of neuronal circuits serving different functions.

# **AUTHOR CONTRIBUTIONS**

Md: study design and coordination, data analysis, and manuscript preparation. KR and AM: EEG and EMG data recording, data analysis. EV: patients selection, data analysis. SI: data analysis, manuscript editing.

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### SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg. 2017.01292/full#supplementary-material

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# Action-Effect Associations in Voluntary and Cued Task-Switching

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The literature of action control claims that humans control their actions in two ways. In the stimulus-based approach, actions are triggered by external stimuli. In the ideomotor approach, actions are elicited endogenously and controlled by the intended goal. In the current study, our purpose was to investigate whether these two action control modes affect task-switching differently. We combined a classical task-switching paradigm with action-effect learning. Both experiments consisted of two experimental phases: an acquisition phase, in which associations between task, response and subsequent action effects were learned and a test phase, in which the effects of these associations were tested on task performance by presenting the former action effects as preceding effects, prior to the task (called practiced effects). Subjects either chose freely between tasks (ideomotor action control mode) or they were cued as to which task to perform (sensorimotor action control mode). We aimed to replicate the consistency effect (i.e., task is chosen according to the practiced task-effect association) and nonreversal advantage (i.e., better task performance when the practiced effect matches the previously learned task-effect association). Our results suggest that participants acquired stable action-effect associations independently of the learning mode. The consistency effect (Experiment 1) could be shown, independent of the learning mode, but only on the response-level. The non-reversal advantage (Experiment 2) was only evident in the error rates and only for participants who had practiced in the ideomotor action control mode.

Keywords: consistency effect, non-reversal advantage, ideomotor action control mode, sensorimotor action control mode, action-effect learning, voluntary task-switching, cued task-switching

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#### INTRODUCTION

Human actions are either exogenously or endogenously controlled (e.g., Herwig et al., 2007; Gaschler and Nattkemper, 2012). In the first case, actions are triggered by external stimulation, i.e., crossing a street because the traffic light turns green or preparing a speech because you are invited to give a presentation. In the latter case, actions are performed to achieve a current goal, i.e., crossing a street because the bookshop to which you want to go is on the other side of the street or booking a train ticket to go on holiday to Amalfi. Thus, in accordance with the stimulus-based approach, humans respond to external stimuli in order to accommodate environmental demands.

Ideomotor approaches emphasize that the cognitive representation of action effects plays a crucial role in action planning (Lotze, 1852; James, 1890/1981; Kunde et al., 2007). According to the ideomotor principle, the motor execution of an action is triggered by the anticipation of the expected action effect. The binding link between sensory events and motor movements has been studied extensively. It is assumed that actions are cognitively represented by codes that capture their sensory events (Prinz, 1990, 1997). In several models of action control,

e.g., Hommel's action-concept model, (Hommel, 1993, 1996) or the theory of event coding (Hommel et al., 2001) action features and sensory events are represented in shared feature codes. As pointed out by Elsner and Hommel (2001) bidirectional learning is an essential precondition for intention-based actions. This means that the learning between (motor) action and (sensory) effect may lead to the activation of a motor response when perceiving the sensory event or endogenously activating its representation. In their two phase-model of action control, motor patterns and sensory effects contingently co-occur (first phase) and are consequently integrated in common coding units (second phase). In line with this theory, Elsner and Hommel's (2001) experiments consisted of two experimental phases: In the acquisition phase, participants pressed a left or a right key with their index fingers either in forced-choice designs (participants were cued as to which key to press) or in freechoice designs (they were allowed to choose which key to press within each trial). Responses were followed by a high or a lowpitched tone depending on the pressed key. In the test phase, the previous action-effects were presented as imperative stimuli before task execution. According to the ideomotor principle, presenting these action effects should activate the representation of these actions. In Experiment 1, they employed a forcedchoice test phase in which participants had to respond to the action effects either with correspondent or reversed tone-key mapping. Subjects performed better with a non-reversed tonekey mapping when compared to reversed mapping (the nonreversal advantage, cf. Pfister et al., 2011). In the following experiments, free-choice test phases were employed. Participants had to randomly choose one of two keys after the previous action-effect was presented. As part of these experiments, subjects selected the key that had produced the presented tone in the acquisition phase. This result pattern is referred to as consistency effect (cf. Pfister et al., 2011).

The acquisition and use of learned action-effect associations have been addressed in numerous studies either employing a freechoice test phase (e.g., Hommel et al., 2003; Hoffmann et al., 2009) or a forced-choice test phase (e.g., Maes, 2006; Hoffmann et al., 2009). In the acquisition phases participants usually performed free-choices between the two response alternatives. As Herwig et al. (2007) and Herwig and Waszak (2009) pointed out, the learning mode in the acquisition phase may also influence the integration of action-effects in the ensuing test phase. Therefore, they contrasted a free-choice acquisition phase with a forcedchoice acquisition phase. By testing the impact of the acquisition phase in a forced-choice test phase, they found a non-reversal advantage for the free choice acquisition group, but not for the forced choice acquisition group. Therefore, Herwig et al. (2007) and Herwig and Waszak (2009), concluded that participants who had undergone stimulus-based learning did not acquire actioneffect links. Experiments on stimulus-response compatibility (Kunde, 2003) and stimulus-effect compatibility (Hommel, 1996) suggest another explanation. It is assumed that participants acquire testable action-effect associations in both learning modes, but only the free-choice acquisition group uses the action-effect links in the test phase. To test this alternative explanation, Pfister et al. (2011) performed the same experiment as Herwig et al.

(2007) but replaced the forced-choice test phase by a free-choice design. If both acquisition groups (free-choice and forced-choice) learned action-effect associations, participants who acquired action-effect binding in the forced-choice group should also show a consistency effect in a free-choice test phase. This is what the authors could show. Their results indicated that the *acquisition* of action-effect associations did not depend on the action control mode in which they were learned. Only the *use* (operationalized in the test phase) seems to be dependent on the action control mode.

As illustrated above, the acquisition and use of action-effect binding under different action control modes have been primarily studied with rather simple choice-reaction tasks in free- and forced-choice designs. Although action-effects are assumed to play a crucial role in response selection, there are only a few studies targeting the impact of action-effects in task selection. Task selection is often studied with the task-switching paradigm. Task-switching reflects the flexibility of the cognitive system when being confronted with multiple task requirements. In everyday life, we often have to decide what to do. Thus, we perform an action in order to achieve a goal by neglecting all the other opportunities that could interrupt the ongoing action. But if a new goal or task is more prominent, the cognitive system must be able to abandon the current task by reconfiguring the current task set in order to select and perform another action.

According to Logan and Gordon (2001) and Logan and Schneider (2010) a task-set can be defined as a set of parameters that program task-specific processes such as perceptual encoding, memory retrieval, response selection, and response execution. If action-effects influence response selection as seen in experiments with free- and forced choice designs, it is conceivable that they will also influence task selection and task execution in task-switching. In a study by Kiesel and Hoffmann (2004), pressing a key (one and the same action) led to two different action effects (short/fast vs. long/slow movements of the target) in a horizontal and vertical arrangement: Reactions were slower in the slow-movement context and faster in the fastmovement context, although the target movements occurred after the response was given. Thus action-effect associations are acquired context specifically and the context influences the way the same action (pressing a key) is performed (slowly or quickly). In a study carried out by Ruge et al. (2010), two target stimuli were horizontally and vertically aligned. A cue indicated whether participants had to determine the position of the horizontal or the position of the vertical stimulus. Two different effect modes followed responses. In the taskrelated effect condition, a red square appeared in the position of the correct response (e.g., left in the horizontal condition or above in the vertical condition). In the task-unspecific effect condition, participants were just told whether they had performed correctly or not. The authors found a significant two-way interaction between task transition and effect type for trials with a long-cued target interval (CTI, i.e., 1500 ms): in the task specific feedback condition, switch costs were reduced. The authors interpret this result as meaning that task-specific feedback can help to disambiguate task-ambiguous

response meanings (that is, the same response for two different tasks).

In order to further study the role of action-effects in taskswitching, Lukas et al. (2013) devised a new paradigm. In an acquisition phase, participants performed magnitude and parity tasks in a cued task-switching paradigm. A cue presented to the target (a number between one and nine without the five) indicated which task to perform. Correct responses were immediately followed by consistently occurring action-effects in the experimental group and by inconsistent, random action effects in the control group. In the transfer phase, the consistently and regularly occurring action-effects changed to a random mapping, so that the learned action-effect associations were no longer valid. If action-effect associations were anticipated and facilitated, implying discrimination between competing task sets, then switch costs should be lower in the experimental group in the acquisition phase and should increase in the transfer phase. This is exactly what Lukas et al. (2013) found - at least for trials with a short cue target interval (CTI). They interpreted the reduced switch costs in the acquisition phase to be due to the fact that participants activate the action effects as part of the current task set. This helps to differentiate competing task sets. However, in trials with long CTIs, the task set is already fully prepared so that there is no additional benefit by consistently occurring task effects. In the test phase, it was shown that switch costs were increased after the learned action-effect associations were no longer valid. This is further evidence that effects that occur as a consequence of an action play an important role, not only in simple-choice designs but also in more complex task designs. Recently, this effect was replicated not only for switch costs, but also for N-2 repetition costs (Schuch et al., 2017). Moreover, it is noteworthy that acquisition as well as the use of action-effect associations could be shown in a design that is comparable to a forced-choice design (neither the task nor the key could be freely chosen by the participants). Herwig and Waszak (2009) already assumed that with more complex S-R mappings, action effects might become more important and hence participants rely more on action-effect associations.

To pursue this thought, we conducted the present study with a cued task-switching paradigm (forced-choice design) and a voluntary task-switching paradigm. Although key strokes in a voluntary task-switching paradigm are not completely freechoice (there is a correct and a wrong response), participants still have the freedom to choose the task they want to perform. Hence, we equalize this paradigm with free-choice designs in simple-response studies. In line with the results obtained by Lukas et al. (2013) and also at least tending in Schuch et al. (2017) with respect to N-2 repetition costs, we assumed that consistent action-effect mappings in the acquisition phase should lead to better performance than randomly assigned action-effects in both task-switching paradigms. However, the main focus of the present study was to investigate consistency effect (i.e., tasks are chosen according to previously learned task-effect associations) and non-reversal advantage (i.e., previously learned task-effect associations improve task performance and switching between tasks when matching effects are presented before task selection) by employing a task-switching paradigm. Thus, we introduced

a cued task-switching paradigm, similar to the forced choice designs (sensorimotor learning mode) and a voluntary taskswitching paradigm similar to the free-choice designs (ideomotor learning mode). In two experiments, participants learned taskresponse-effect associations either in a cued or in a voluntary task-switching design. In Experiment 1, consistency was tested by presenting the previous learned action-effects before task selection in a voluntary task switching paradigm (to distinguish the preceding "action"-effects better from the action effects in the acquisition phase, they are called practiced effects in the following). In line with consistency effect, subjects should tend to choose the task that was previously followed by the respective effect. In Experiment 2, the non-reversal advantage was tested by presenting the previous learned action-effects before the task cue. In line with non-reversal advantage, subjects should react faster and be less error prone when the respective practiced effect matches the following task. Moreover, we were interested in determining whether the integration of action effects in a task set is limited to the response level or takes place on a higher hierarchical task level. That means, for instance, that participants have learned the association between pressing a certain key and the screen turning to green for numbers smaller than five. When, during the test phase, the practiced effect is a screen turning to green and the target number is greater than five, they are more likely to press the key assigned in which the screen turns to yellow when task-effects are integrated on the task level.

#### **EXPERIMENT 1**

#### **Materials and Methods**

#### **Participants**

Eighty participants (59 female, 21 male) took part in Experiment 1 (age range 18–29, M=21.4, SD=2.3). The subjects were randomly assigned to experimental and control groups in both learning modes (ideomotor learning – voluntary taskswitching vs. sensorimotor learning – cued task-switching). The experimental groups received consistent, predictable actioneffects, whereas the control groups received random, non-predictable action-effects. Hence, in the control groups, no action-effect learning could take place (see paragraph Stimuli, tasks and action effects for further explanation).

Subjects were undergraduates who either received partial course credit or a monetary reward of 10 € each. Ethical approval was not required for this study in accordance with national and institutional requirements. All procedures performed in this study were in accordance with the ethical standards of the 1964 Helsinki declaration and its later amendments. Informed consent was obtained from all individual participants.

#### Stimuli, Tasks, and Action Effects

The experiment was programmed in PsychoPy, v1.83.01 (s. Peirce, 2007, 2009) and ran on a Baron Shuttle PC (CPU 3.5 GHz). Stimuli were presented on a Dell monitor with a display diagonal of 22". Participants sat in front of the screen at a viewing distance of approximately 60 cm. The stimuli consisted of digits ranging from one to nine without a five. They appeared in white

on a black background in the center of the screen with a height of 1.3 cm (visual vertical angle 1.24°). Participants had either to decide whether a number was larger or smaller than five (magnitude task) or whether it was odd or even (parity task). For one task, they had to press the period-key and the y-key with the right and left index finger, for the other task they had to press the q-key and the p-key with the right and left middle finger. The keys arranged on the left side of a standard QWERTZ-keyboard were always assigned to odd or less than five, and the keys arranged on the right side were assigned to even or greater than five. The task-key assignment was counterbalanced across participants.

Participants of the ideomotor learning groups (*EG 1* and *CG 1*) were instructed to choose between one of two tasks based on these instructions: "In this experiment you have to perform one of two tasks, the magnitude task or the parity task [...]. You yourself may choose which task you are going to perform next. Keep in mind that you must switch regularly, so that you are performing the two tasks in an approximately equal proportion."

In the sensorimotor learning groups (EG 2 and CG 2), participants were cued as to which task to perform. The cues were a square or a diamond that framed the stimulus. The square indicated the parity task, the diamond the magnitude task. First, a fixation cross appeared in the middle of the screen for 500 ms. Immediately after, the cue was presented and 500 ms later the stimulus appeared (CTI = 500 ms). Cue and stimulus stayed on the screen until a response was obtained. If there was no response after 2500 ms, they disappeared and a message appeared, prompting participants to respond faster. If participants pressed the wrong key, an error message appeared. The error message was displayed on the screen for 500 ms immediately after the wrong response with a letter height of 0.3 cm (during the acquisition phase and the relearn block). In the test phase, errors were indicated on the screen with a more prominent letter height of 1.3 cm. Only correct responses were immediately followed by action-effects. For one task, a large green or yellow square (19.5 cm in length) appeared as

action effect on the screen for 500 ms and a high or a lowpitched tone was emitted for 500 ms for the other task. On the response level, the action effects differed in regard to their features (green, yellow, high or low). The action-effects differed also on a higher dimensional level, i.e., for one task visual action effects appeared and for the other task auditory action effects appeared. The assignment of tasks and action-effects (e.g., visual/magnitude task, auditory/parity task) was counterbalanced across participants (see for example Figure 1). The green square and the deep tone were always assigned to the responses "even" or "smaller." The yellow square and the high tone were always assigned to the responses "odd" or "larger," respectively. In the control groups (CG 1 and CG 2), action-effects were randomly assigned. Each response-effect combination was possible with equal probability. Therefore, there was no consistency between response and effects, neither on the response level nor on the task

In the test phase of both experiments, the practiced effects were presented before task selection. Every practiced effect could now be followed by any target. That is, 32 combinations of practiced effect and target were possible, of which half of them were learned associations and half of them had not been associated before. For instance, the low tone was associated with the response "smaller" and hence with small target numbers, but never with larger target numbers. A low tone followed by the number 9 would hence be an unknown association. The practiced effect (presented for 500 ms) was followed by the target after a gap of 200 ms (i.e., inter-stimulus interval [ISI] = 700 ms). Participants were instructed to freely choose which task to perform. After correct responses, the screen stayed black for 900 ms. If the response was wrong, an error message appeared on the screen for 500 ms. The screen turned black for a further 400 ms until the next trial began. After each block, participants received feedback concerning their mean response time and the amount of correctly executed tasks. They were reminded to respond as quickly and correctly as possible.

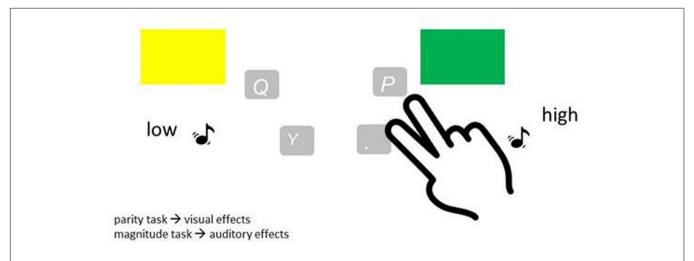


FIGURE 1 | Example of a task-effect assignment for the experimental groups. Performing one task (here: the parity task, which was executed with the response keys q and p) elicited visual action effects, the respective other task (here: the magnitude task, executed with the response keys y and period) auditory action effects.

#### Procedure and Experimental Design

Participants were instructed in written form and additionally orally if further explanation was needed. The experimental group was not explicitly informed about the action-effect association. Both groups were told that they could use the action-effects as feedback if the task was performed correctly, because after a wrong response, no action-effect occurred. Moreover, they were asked to respond as quickly and as correctly as possible.

The session started with a short practice block consisting of 16 trials, which were not registered. The experiment consisted of seven blocks of 64 trials: five acquisition blocks, in which the subjects learned action-effect associations and two test blocks, in which the effect of the learned associations was tested. After the fourth acquisition block, the first test block was conducted (Block 5). Subsequently, the fifth acquisition block (Block 6) was presented, functioning as a relearn block, and serving as an update for learned action-effect associations (see **Figure 2**). Finally, the second (and last) test block (Block 7) was performed.

Several analyses were conducted to test different hypotheses. In Experiment 1, the focus was on the consistency effect. For that reason, the task-choice ratio for consistent tasks was tested in the test phase as a dependent variable. A chosen task was defined as consistent when it matched the practiced effect according to the previously learned action-effect association. That is, the task followed by a visual effect in the acquisition phase was also chosen when a visual effect preceded the task stimulus. Condition (experimental vs. control) and learning mode (voluntary task-switching vs. cued task-switching) were between-subject independent variables. For performance measurements,

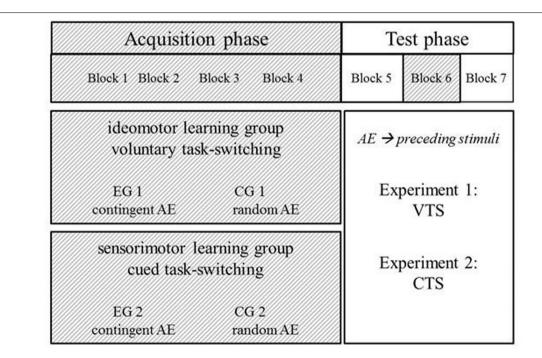
RT and error rate were dependent variables, and task transition (repetition vs. switch) and block (acquisition blocks vs. test blocks) were independent variables.

#### Results

#### Consistency Effect

To analyze the consistency effect, first, the amount of task-consistent vs. inconsistent task choices was enumerated. Although no consistent response-effect associations could be seen in the control groups, their responses were categorized as "task-consistent and task-inconsistent" in the same way as the responses of the parallelized experimental groups. That is, if the experimental group had experienced that the response "even" elicited a green square, choosing the parity task (by answering with the odd or even key) was considered as task consistent. In the same way, also the task choice of the control group was categorized (choosing the parity task after a green square is "task consistent"), although the control group had no association between a green square and the response "even."

Participants in the voluntary task switching blocks who performed less than five switches or repetitions in the acquisition phase or performed one task only more than 54 times in either in an acquisition block or in a test block (comprising 64 trials) were excluded from analyses. 34 (of 80) participants met these criteria. In the voluntary task switching group, 8 control and 13 experimental condition participants had to be excluded. In the cued task switching group, 5 control and 8 experimental condition participants had to be excluded. The distribution of remaining participants in each condition is shown in **Table 1**.



**FIGURE 2** | Experimental design for both experiments: *CG* 1 and *CG* 2 – control groups, *EG* 1 and *EG* 2 – experimental groups. 1 stands for voluntary task-switching (VTS), 2 for cued task-switching (CTS), AE for action effects. In Experiment 1, the test phase was voluntary task switching, in Experiment 2, the test phase was cued task switching. In the test phase, action effects became preceding effects (practiced effects).

**TABLE 1** | Distribution of participants in Experiment 1 in each condition after selection.

Condition in the acquisition phase	Participants
Voluntary task switching, experimental	10
Voluntary task switching, control	9
Cued task switching, experimental	13
Cued task switching, control	12

Trials in which errors were committed and trials following these were also excluded. On average, 16.2% of the trials were erroneously performed. A two-way ANOVA with the independent between-subject variables condition (experimental vs. control) and learning mode (voluntary task switching vs. cued task switching) and the dependent variable task-choice ratio of consistent tasks (in percent) was conducted.

The main effect condition only tended to be significant, F(1,40) = 3.18, p = 0.08,  $\eta_p^2 = 0.07$ . Participants in the experimental groups made task-consistent task choices in 54.5% (SE = 2.6). Participants in the control groups made task-consistent task choices in 47.7% (SE = 2.8). Task consistent choice ratio did not differ significantly from 50% in both groups (t[22] = 1.4, p > 0.05 for the experimental groups and t[20] = -2.0, p > 0.05 for the control group). Neither the main effect learning mode, F < 1, nor the interaction between condition and learning mode were significant, F < 1.

In order to take a closer look at the consistency effect, we conducted two additional two-way ANOVAs. In a voluntary task-switching paradigm, comprising two tasks, participants were allowed to choose between two correct responses. In the test phase, that means that the responses can be task consistent or task inconsistent with respect to the practiced effects. Moreover, task consistent responses can be response consistent or response inconsistent. For instance, a green square was associated with the response "even" in the acquisition phase. In the test phase, however, it was possible for a green square to be followed by the number 7. These two stimuli have never been associated before because 7 is an odd number. However, if the participant still chose to perform the parity task, this trial was task consistent, but response inconsistent. Trials in which the practiced effect and a possible correct response match the formerly learned action-effect associations are both task consistent and response consistent. Task and response consistent trials were analyzed separately from other trials. The expected resulting pattern from choosing responses consistent with the former learned action-effect associations would suggest that task-effects are integrated in a task set on the response level. Analyzing the other trials, in which neither of the correct responses matched the learned response-effect associations, should provide evidence as to whether action-effects are also integrated on a higher task level. Although not matching on the response level, the response in which the associated action-effect shares the same modality as the practiced effect fits on the task-level. We assumed that pressing these keys in a non-random manner may show that task-effects are not just associated to the motor response patterns for pressing a key, but

also integrated into the mental representation of the numerical categorization.

#### Analysis on the Response Level

In those trials in which correct responses matched formerly learned action-effect associations, participants of the experimental groups made response consistent choices in 27.9% (SE=1.3) of the trials (please note that only 25% of all trials provide the possibility to be task compatible as well as response compatible). The control groups chose the matching response in 23.8% (SE=1.4) of the trials. The difference in task-choice ratio was reflected by a main effect condition, F(1,40)=4.6, p<0.05,  $\eta_p^2=0.1$ . Neither the main effect learning mode, nor the interaction between condition and learning mode was significant, Fs<1.

#### Analysis on Task Level

In those trials in which neither of the correct responses matched formerly learned action-effect associations on the response level, participants of the experimental groups made task consistent (but response inconsistent) choices in 26.6% (SE=1.5) of the trials (please note, that like above, only 25% of all trials provide the possibility to be task compatible, but response incompatible). The control groups chose this response-effect pattern 23.9% (SE=1.6) of the time. This difference was not significant. Neither the main effect condition, nor the main effect learning mode, nor the interaction between condition and learning mode were significant, Fs<1.6.

Since by means of standard null-hypothesis testing the non-existence of an effect may not be confirmed, we additionally applied a Bayesian alternative developed by Wagenmakers (2007) as suggested by Masson (2011). The BIC, an index commonly used to quantify goodness-of fit of a formal data model, is applied for generating an estimate of the Bayes factor, BF  $\approx \frac{p \text{BIC}(\text{D}|\text{H}_0)}{p \text{BIC}(\text{D}|\text{H}_1)} = e^{(\Delta \text{BIC})/2}$ . The calculation yielded a Bayesian factor of BF = 3.0.

The posterior probability favoring the null-hypothesis, that there is no effect condition on task-choice ratio, was  $p_{\rm BIC}({\rm H_0}|{\rm D}) = \frac{{\rm BF}}{{\rm BF}+1} = 75\%$ . The subsequent probability, favoring the alternative hypothesis, that participants in the experimental groups would make more consistent task-choices than that of the control groups, was  $p_{\rm BIC}({\rm H_1}|{\rm D}) = 1 - p_{\rm BIC}({\rm H_0}|{\rm D}) = 25\%$ .

To provide comparability to the *BF* on the task level, also the *BF* on the response level was calculated and yielded a BF = 0.7. The posterior probability favoring the null-hypothesis that there is no effect on the response level was  $p_{\rm BIC}$  (H<sub>0</sub>|D) = 42%. Consequently, the posterior probability favoring the alternative hypothesis was  $p_{\rm BIC}$  (H<sub>1</sub>|D) = 58%.

#### Discussion of Experiment 1

The results of Experiment 1 showed indeed that participants in the experimental groups favored tasks that were previously associated with the stimulus that now preceded the task choice. However, this was only significant on the response level. That is, only when the practiced effect and the target had been associated before and hence allowed a previously associated response, was it possible to see a choice in favor of the matching task. If practiced

effect and target had not been previously associated, it was not possible to see a choice in favor of the task that was associated with the practiced effect. Hence there is doubt as to whether real task-effect associations do occur. Our results at least indicate a stimulus-response-effect association on a lower hierarchical level. However, one can also not state that no real task-effect associations exist. The Bayesian factor only shows weak evidence for favoring the null-hypothesis. Due to the large amount of subjects that had to be excluded, we lost test power in no small measure. Therefore one can also argue that the effect was too small to be detected by the remaining sample size.

#### **EXPERIMENT 2**

#### **Materials and Methods**

#### **Participants**

Seventy-five participants (50 female, 25 male) took part in Experiment 2 (age range 18–37, M = 20.6, SD = 2.3). As in Experiment 1, the sample consisted of undergraduates who either received partial course credit or a monetary reward of  $10 \in$ .

#### Stimuli, Tasks, and Action Effects

Stimuli, tasks and action effects were designed in a similar way to Experiment 1. The acquisition phase was exactly the same as in Experiment 1. The difference between Experiment 1 and Experiment 2 was the test phase. In Experiment 1, we focused on the consistency effect. In Experiment 2, attention was focused on the non-reversal advantage. For this reason, in the test phase, the formerly learned action effects turned to preceding practiced effects with a cued task-switching design. The practiced effect was presented for 500 ms. After the practiced effect disappeared, 200 ms later the task cue and the target were simultaneously presented. As in Experiment 1, the cues were a square or a diamond that framed the stimulus.

#### Procedure and Experimental Design

The procedure was the same as in Experiment 1. However, the analyses differed, as the focus was on the non-reversal advantage. Data from the test phase (Block 5 and Block 7) of Experiment 2 were analyzed using a three-way ANOVA with the between subject variables condition (control vs. experimental), learning mode (voluntary vs. cued task-switching) and task consistency (task-consistent vs. task-inconsistent). Dependent variables were RT and error rate.

#### **RESULTS**

#### Non-reversal Advantage

Like in Experiment 1, participants in the voluntary task switching blocks who performed less than five switches or repetitions in the acquisition phase were excluded from analyses. Participants who did not show any (correct) switch trials in two or more blocks of the acquisition phase or who failed to switch correctly in one or both test blocks were excluded from analyses due to not following instructions. 18 participants of 75 were

excluded from analyses, all of them were in the ideomotor learning group, 9 in the experimental and 9 in the control group (see **Table 2** for distribution in each condition for the remaining participants). For RT analysis, trials in which errors were committed and trials following these were also excluded. Furthermore, all trials exceeding three standard deviations above the mean of RT and trials with an RT of less than 200 ms were omitted

#### RT

Mean values in every condition and SE are shown in **Table 3**. None of the main effects reached significance, Fs < 1. Likewise, none of the two-way interactions reached significance, Fs < 1. The three-way interaction of condition, learning mode and task consistency, however, tended at least to be significant, F(1,54) = 3.1, P = 0.08,  $\eta_P^2 = 0.05$ . Numerically, participants who had performed voluntary task switching in the acquisition phase were faster in task consistent trials than in task inconsistent trials. The BF of the three-way interaction is 1.6, resulting in a  $p_{\rm BIC}$  (H<sub>0</sub>|D) = 62% and a  $p_{\rm BIC}$  (H<sub>1</sub>|D) = 38%.

#### **Error Rate**

Error rate data were first arcsine transformed, before being entered into the three-way ANOVA with the variables condition, learning mode, and task consistency (see Figure 3). The main effect of task consistency was significant, F(1,54) = 6.98, p < 0.05,  $\eta_p^2 = 0.11$ . Task consistent trials yielded fewer errors (29.6%) than task inconsistent trials (34.4%). The main effect of learning mode was also significant, F(1,54) = 54.0, p < 0.001,  $\eta_p^2 = 0.5$ . Participants, who had performed voluntary task switching in the acquisition phase, showed a higher error rate (47.8%) compared to participants who performed cued task switching (16.2%). Likewise, the interaction of task consistency and learning mode was significant, F(1,54) = 8.25, p < 0.01,  $\eta_p^2 = 0.13$ . Only in the voluntary task switching learning mode, task consistent trials yielded fewer errors than task inconsistent trials (43.0% vs. 52.6%), in the cued task switching learning mode, the error rates were the same (16.2% vs. 16.1%). The two-way interaction of task consistency and condition just failed significance, F(1,54) = 3.9, p = 0.052,  $\eta_p^2 = 0.07$ . In the experimental groups, the error rate was reduced to a higher amount for task-consistent trials (28.6% vs. 36.6%) compared to the control group (30.7% vs. 32.2%). The main effect of condition was not significant (F < 1). The three-way interaction of condition, learning mode and task consistency only tended to be significant, F(1,54) = 3.0, p = 0.09,  $\eta_p^2 = 00.05$ . The BF of this three-way interaction was 1.7,  $p_{BIC}(H_0|D) = 63\%$  and a  $p_{BIC}(H_1|D) = 37\%.$ 

**TABLE 2** | Distribution of participants in Experiment 2 in each condition after selection.

Condition in the acquisition phase	Participants
Voluntary task switching, experimental	12
Voluntary task switching, control	10
Cued task switching, experimental	18
Cued task switching, control	18

TABLE 3 | Mean RT (and SE) in ms in the test phase as a function of condition, learning mode and task consistency.

			Task cor	nsistency
		Learning mode	Task consistent	Task inconsistent
Condition	Experimental	Voluntary task switching	918 (54)	956 (55)
		Cued task switching	1056 (44)	1056 (45)
	Control	Voluntary task switching	933 (59)	902 (60)
		Cued task switching	1020 (44)	1047 (45)

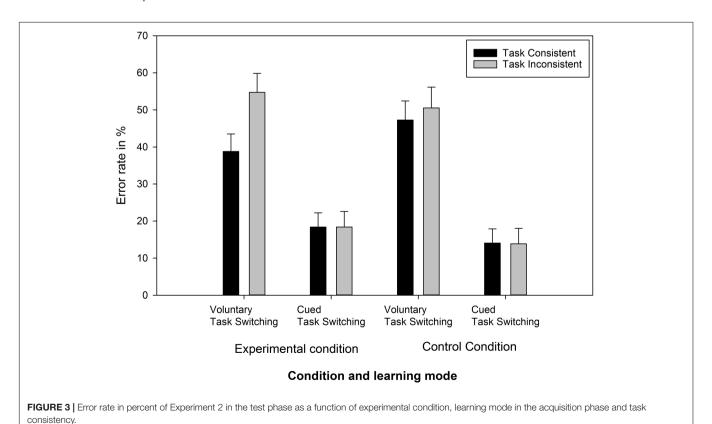
#### Reaction Time and Error Rates in the Acquisition Phase

Since the acquisition phase and the relearning block of both experiments were the same, data from both experiments were merged to analyze whether consistent action-effects in a voluntary and cued task-switching paradigm would reduce performance costs. For reaction time analysis error trials and trials following an error trial were excluded from analyses. All trials that exceeded three standard deviations of the mean RT or had a RT of less than 200 ms were omitted. Moreover, the same participants that had been excluded from analysis in Experiment 1 and Experiment 2 were excluded.

#### RT

A three-way ANOVA with the variables condition, learning mode and task transition revealed a main effect of condition, F(1,98) = 4.7, p < 0.05,  $\eta_p^2 = 0.05$ . Participants in the experimental

groups were faster (704 ms) than participants in the control groups (758 ms). The main effect of task transition was also significant, F(1.98) = 68.7, p < 0.001,  $\eta_p^2 = 0.41$ . Participants reacted slower in switch trials (769 ms) compared to repetition trials (692 ms). The two-way interaction of condition and task transition was also significant, F(1.98) = 4.8, p < 0.05,  $\eta_p^2 = 00.05$ . Switch costs were higher in the experimental conditions (97 ms) than in the control conditions (57 ms). Likewise, the two-way interaction of learning mode and task transition was significant, F(1,98) = 5.3, p < 0.05,  $\eta_p^2 = 0.05$ . Switch costs were lower in the voluntary task switching mode (55 ms) than in the cued task switching mode (98 ms). There was also a twoway interaction of condition and learning mode, F(1,98) = 8.0, p < 0.01,  $\eta_p^2 = 0.07$ . With consistent action-effects (experimental condition), participants performing voluntary task-switching were faster (676 ms) than participants with random action effects (control condition; 799 ms). Participants performing cued taskswitching showed similar RTs in the experimental and control



condition (732 ms vs. 716 ms). The main effect learning control mode was not significant, F < 1, neither was the three-way interaction between condition, learning mode and task transition, F < 1.

#### **Error Rate**

Concerning the error rate, first the data were arcsine transformed and then the same three-way ANOVA as for the RT was applied. The main effect of condition was significant, F(1,98) = 4.7, p < 0.05,  $\eta_p^2 = 0.05$ . Participants receiving consistent action effects yielded fewer errors (10.4%) than participants receiving random action effects (14.6%). Like for the RT, also the main effect of task transition was significant, F(1.98) = 31.2, p < 0.01,  $\eta_p^2 = 0.24$ . Participants made fewer errors in repetition trials (11%) than in switch trials (14%). The two-way interaction of condition and learning mode was significant, too, F(1,98) = 15.7, p < 0.01,  $\eta_p^2 = 0.14$ . Participants in the voluntary task switching mode were less error prone in the experimental condition than in the control condition (6.9% vs. 19.2%). In contrast, participants in the cued task switching mode showed numerically less errors in the control condition (10%) than in the experimental condition (14%). No other main effect or interaction was significant, Fs < 1.

#### **Discussion of Experiment 2**

Concerning RT, the non-reversal advantage could not be shown, but it was seen in the error rates. Task consistent trials vielded fewer errors than task inconsistent trials. This effect was qualified by the two-way condition of task consistency and learning mode. Only in the voluntary task switching learning mode, task consistent trials yielded fewer errors than task inconsistent trials (43.0% vs. 52.6%). In the cued task switching learning mode, the error rates did not differ (16.2% vs. 16.1%). It is also seen that the error rates of the voluntary task switching mode was much higher in the (cued) test phase than of the cued task switching learning mode. This effect was only seen in the two test phases. Hence it cannot be traced back to a general error in the experimental procedure, nor to a lack of motivation of the participants. It seems that the shift from a voluntary task switching design (in which two of four task keys were correct) to a cued task-switching design (in which only one of four task keys is correct) causes strong confusion, requiring high cognitive effort and leading to a high error rate. Although there are several studies that combine freechoice tasks with forced-choice tasks (e.g., Fröber and Dreisbach, 2017; Naefgen et al., 2017), those different tasks were rather intermixed and participants were aware of both task types. In our case, those participants who were trained in a voluntary taskswitching paradigm did not know they would have to shift to a cued task-switching paradigm. Whether this unawareness alone causes the high amount of errors or whether the required high cognitive effort to suppress formerly learned correct responses as wrong responses alone leads to this effect cannot be answered in this study and requires further research.

Analyses of RT and error rate revealed a general performance improvement with consistent action effects compared to random action effects. This effect was only seen in the voluntary task switching mode. Participants were fastest in the voluntary task-switching design. This is noteworthy, as usually free-choice tasks

are executed more slowly than forced-choice tasks (e.g., Naefgen et al., 2017). This usual pattern was also seen in the control conditions. Action effects seem to have a general facilitating effect in voluntary task switching. This facilitating effect was mainly seen in task repetition trials. This is why in the present study, switch costs were affected only negatively, at least concerning RT. Hence, we failed to replicate findings in which action effects helped specifically to distinguish task set and led to decreased switch costs (e.g., Ruge et al., 2010; Lukas et al., 2013).

#### **GENERAL DISCUSSION**

In the current study, we targeted whether action-effects are involved in task selection and execution under different actioncontrol modes (sensorimotor vs. ideomotor). For this reason, three measurements were analyzed: consistency effect, which reflects whether bi-directional learning also occurs in task selection, non-reversal advantage, which shows if task execution is facilitated when combined with task-consistent practiced effects, and task performance (RT, error rate and switch costs) when action effects are consistent compared to when they are completely random. Participants learned stable action-effect associations in a task-switching paradigm in the experimental groups, while the control groups performed completely random action-effects that could not be anticipated. Two action-control modes were used in those acquisition phases: a voluntary taskswitching design, in which participants followed an ideomotor learning mode, and a cued task-switching design, in which participants followed a sensorimotor learning mode.

#### **Consistency Effect**

In Experiment 1, the previously learned action effects turned to practiced effects in the test phase. The test phase consisted of a voluntary task-switching paradigm. The ratio of the chosen tasks that matched the previously learned task-effect association was analyzed (i.e., consistency effect). It was shown that participants chose responses matching formerly learned response-effect mappings in greater number than those due to random effects. This was independent of the learning mode. That is, we can confirm that the acquisition of action-effect associations takes place in a more complex task environment in sensorimotor as well as in ideomotor learning modes (cf. Pfister et al., 2011).

By splitting up the data in the test phase of Experiment 1, we found that participants selected responses that matched previously learned stimulus-response-effect-associations above random response rates. However, participants did not select tasks according to task-effect associations. Sharing the same modality did not seem to be sufficient to link to one task (i.e., visual effects are linked to the parity task). Accordingly, the integration of sensory effects in the task-set of the numerical selection tasks, applied in this study, seems to take place on a response level and thus prompts the key-press (the goal-directed movement) and not the mental categorization *per se.* This does not mean that task-effect associations do not exist. However, in this study they were too weak to show evidence for bi-directional task-effect

associations. It is for instance conceivable that task effects need to be task-relevant or that tasks and effects have a logic relation to one another. Hence, the mechanisms underpinning the retrieval process are still not clear. Referring to feature-integration theory, the preceding stimuli trigger the response only on condition that there is a complete feature overlap. If under the same condition (e.g., number less than five), there is a feature-mismatch (the color of the preceding stimulus is yellow and not green as in the acquisition phase), the response belonging to the matching task (magnitude) is not prioritized. Further research is necessary in order to determine whether the retrieval mechanisms of task-effects work in an all-or-none manner or rather in a manner of graded/weighted correspondence/overlap.

#### Non-reversal Advantage

In Experiment 2, the non-reversal advantage was the focus of interest. The acquisition phase was exactly as in Experiment 1, but the test phase consisted of a cued task-switching paradigm. The cued task was preceded by formerly learned action effects. We analyzed whether task performance was facilitated when the preceding effects matched formerly learned action-effect associations. Regarding RT, there was only a small hint with a tendency that participants who had acquired action-effect associations in an ideomotor learning mode reacted faster in task consistent trials. The results of the error rate support this tendency. Task-consistent trials were less error prone than task inconsistent trials only in the ideomotor learning groups and rather for the experimental groups. There are several explanations as to why the effect of non-reversal advantage was not clearer. The main problem is, as mentioned above, the loss of power due to much exclusion of participants from analyses. Moreover, with respect to the non-reversal advantage one has to keep in mind that in earlier studies (e.g., Elsner and Hommel, 2001; Herwig and Waszak, 2009) the preceding effect itself served as an imperative stimulus and no additional cue was presented. It is possible that the cue in the cued task-switching paradigm overlaps the non-reversal advantage. Maybe the non-reversal advantage would be more prominent if the practiced effect itself would serve as cue.

Also the CTI has to be taken in consideration with respect to the results. In the Lukas et al. (2013) study, two different CTIs had been applied. The worsening effect of task-switch costs when changing consistent action effects into random action effects was only seen in the condition with short CTI. Schuch et al. (2017) used a CTI of 500 ms. They found clear effect of increased switch costs only in the error rate. In the present study, the CTI was also 500 ms in the acquisition phase and even longer (700 ms) in the test phase. It is possible that the effect of action effects in task switching is transient and other cognitive processes take over control in task performance with longer CTI.

#### **Task Performance**

Analyses of the acquisition phase revealed that action effects especially help task performance in a voluntary task-switching paradigm: RT is faster with consistent action effects during voluntary task-switching. Usually, free-choice tasks are performed slower than forced-choice tasks, as they are

accompanied by additional cognitive processes. It is assumed that these processes reflect generating internally a task goal (see Naefgen et al., 2017). Providing action effects in a voluntary task-switching paradigm might accelerate this goal generating process.

Previous studies have shown that action effects can help to create task-ensembles (Weaver and Arrington, 2013). Although no task-ensembles were used in the presented study, but only a flat non-hierarchical task structure (to each task and each response belonged one specific effect), it was assumed that action effects in a voluntary task-switching paradigm can contribute in reducing switch costs, as has been shown by previous studies with a forced-choice task switching paradigm (Ruge et al., 2010; Lukas et al., 2013). However, we found larger switch costs for the groups with consistent action effects than for the groups with inconsistent action effects. Likewise, in the study of Lukas et al. (2013), the comparison took place between "predictable action effects" and "random, non-predictable action effects." In the study of Ruge et al. (2010) the comparison took place between "task-related effect feedback" and "non-specific accuracy feedback." But in both studies, a forced-choice taskswitching paradigm was conducted. Hence, one could assume that in a voluntary task-switching paradigm, action effects are not helpful to reduce switch costs. This assumption, however, is in contrast to the assumption that action effects are especially effective in an ideomotor action control mode (e.g., Pfister et al., 2010, 2011; Herwig and Waszak, 2012). In the present study, action effects seemed to be especially efficient to reduce RT of repetition trials, hence increasing switch costs. Further research is needed to investigate under which conditions action effects can reduce switch costs by also reducing the RT of the switch trials.

The absent effect of reduced switch costs, however, does not lessen the effect action effects have on task selection. Also Arrington and Yates (2009) and Arrington et al. (2010) proposed that task selection and task performance are independent of each other. The differentiated effects only provide further evidence for this assumption.

#### CONCLUSION

The results of our study broaden this previous research by applying and combining two different task-switching paradigms with action effects: a cued task-switching paradigm and a voluntary task-switching paradigm. In previous research it was shown that action effect associations of simple response-effect associations were learned in both learning modes: ideomotor and sensorimotor control (Pfister et al., 2011), but evidence for the use was only seen in the ideomotor control mode. Accordingly, we find that the consistency effect was found independently of how action-effect associations were learned, but only on the response level. That is, only when the practiced effect and possible responses had been associated before, the matching response is selected. Concerning the non-reversal advantage, we find support for the idea that the mode in which action-effect association are learned in more complex environments affect task performance

differently. Whether this means that two different action control systems underlie this effect cannot be answered with this study. Janczyk et al. (2015b) for instance argue against the separation of two action control systems. Although we cannot reject this statement based on our results, the debate of how learning mode affects task performance is not yet completed.

Janczyk et al. (2015a) question whether free-choice tasks are an appropriate method to study voluntary actions. One might also raise the question with respect to our study. We argue that it was exactly the underlying task (and the accompanying higher cognitive effort) that we wanted to investigate with respect to action-effect learning. Although we are not convinced that it is completely inappropriate to study action control with voluntary responses, we concede that one might consider alternative research methods in the future.

To sum up, it was shown that specific action-effect association were used for task selection in more complex task environments. Evidence for non-reversal advantage was rather shown for error rate. Action effects help to reduce reaction time in a voluntary task switching paradigm, but switch costs are not affected.

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#### **AUTHOR CONTRIBUTIONS**

AS and SL designed the study. AS executed data collection. SL analyzed the data. AS wrote a first draft of the manuscript, SL revised it.

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# Adoption of Task-Specific Sets of Visual Attention

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Evidence from behavioral and physiological studies suggests attentional weighting of stimulus information from different sources, according to task demands. We investigated the adoption of task-specific attentional sets by administering a flanker task, which required responding to a centrally presented letter while ignoring two adjacent letters, and a same-different judgment task, which required a homogenous/heterogeneous classification concerning the complete three-letter string. To assess the distribution of attentional weights across the letter locations we intermixed trials of a visual search task, in which a target stimulus occurred randomly in any of these locations. Search task reaction times displayed a stronger center-to periphery gradient, indicating focusing of visual attention on the central location, when the search task was intermixed into blocks of trials of the flanker task than into blocks of trials of the same-different task (Experiment 1) and when a cue indicated the likely occurrence of the flanker task as compared to the likely occurrence the same-different task (Experiment 2). These findings demonstrate flexible adoption of task-specific sets of visual attention that can be implemented during preparation. In addition, responses in the intermixed search task trials were faster and (marginally significantly) more error-prone after preparation for a (letter) task repetition than for a task switch, suggesting that response caution is reduced during preparation for a task repetition.

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#### INTRODUCTION

In task switching studies participants frequently alternate between different choice reaction time (RT) tasks afforded by the same stimuli. These studies have provided ample evidence that task performance, in particular in task switch trials (i.e., trials in which the to-be-executed task differs from the task of the directly preceding trial), benefits from increasing the length of a preparation interval during which participants have foreknowledge about the identity of the upcoming task (for overviews, see Karayanidis et al., 2010; Kiesel et al., 2010). This facilitation is usually attributed to *task-set preparation*, that is, to a set of processes that configure the cognitive system to a state that enhances speed and/or accuracy of processing an upcoming stimulus according to the requirements of the currently relevant task. Task preparation thus constitutes an important means to enhance processing efficiency, particularly in conditions of changing task requirements for which it cannot be assumed that a state of task-specific readiness is simply carried over from previous application.

Tasks typically used in task switching experiments, albeit cognitively simple, involve a variety of different components as possible candidates for preparatory optimization, and the precise set of components may depend on the specific combination of tasks between which switching is required. A frequent situation involves tasks associated with perceptually different target dimensions, such as shape and color. Task preparation in such a context may involve biasing attentional weights in favor of the upcoming task's target dimension, resulting in speedup of extraction of the relevant stimulus features. Although some models of task switching incorporate such attentional biasing (e.g., Meiran, 2000; see also Logan and Gordon, 2001; Meiran et al., 2008), preparation-related facilitation of task processing might, alternatively, reflect a speed-up of postperceptual processes that transform an abstract mental code derived from the relevant perceptual attributes of the stimulus into the task-appropriate response code. Given that preparation benefits are also observed in task switching situations in which tasks do not differ regarding the relevant perceptual attributes of the stimuli (e.g., switching between classifying visually presented digits regarding their parity versus their magnitude, Schuch and Koch, 2003), assuming a post-perceptual locus of the preparation effect might be considered a more parsimonious account.

On the other hand, evidence suggesting directing of attention to a perceptual target stimulus dimension during preparation has been obtained in visual search studies. Specifically, using cross-dimension singleton search, in which participants have to detect a feature singleton that occurs randomly in one of two or more distinct perceptual dimensions, such as color or orientation, Müller H.J. et al. (2003) demonstrated that search performance benefits from advance cuing of the upcoming target's perceptual dimension. Because the number of targets used in each perceptual dimension was limited, the cue not only indicated the perceptual dimension of the upcoming target but also constrained the set of possibly upcoming targets (e.g., to a line tilted by one of three possible degrees when the cued dimension was orientation) as well as of the upcoming S-R relation (e.g.,  $45^{\circ}$  left  $\rightarrow$  left key,  $90^{\circ}$  $\rightarrow$  central key, 45° right  $\rightarrow$  right key), thus allowing for a nonperceptual locus of the cuing benefit. This criticism seems difficult to apply, however, to the observation of cue-based facilitation for all targets of a dimension when the cue indicated only one of them as likely to occur.

Another argument supporting preparatory adoption of attentional sets that bias processing toward the perceptual target dimension of an upcoming task relates to cuing effects observed in task switching studies in which the tasks do not differ regarding their (instructed) S-R rules. Specifically, benefits of advance task cuing have also been found when participants switched between a Stroop task (Stroop, 1935) that requires naming the print color of a color word and the complimentary task of word reading, or between responding to the global versus the local letter of a hierarchical (Navon) stimulus (Navon, 1977) with a constant letter-response assignment (e.g., H  $\rightarrow$  left key, S  $\rightarrow$  right key) (Hübner, 2000; Lamb et al., 2000). Inferring preparatory biasing of stimulus dimensions from these findings appears straightforward if task processing in such situations is characterized by, first, transforming the relevant perceptual

attribute (e.g., red color or the letter string RED) into an abstract code which is then subjected to the same S-R translation process. However, extant models have tended to assume different, task-specific, sets of S-R translation processes even for these cases (e.g., Gilbert and Shallice, 2002), thus allowing a post-perceptual locus of the cuing benefit.

In summary, although adjustment of attentional weights given to the currently relevant and irrelevant perceptual stimulus dimensions appears to be a likely means of preparation when switching between tasks, experimental evidence that cannot alternatively be accounted for in terms of the activation of task-specific (post-perceptual) S-R translation processes is widely lacking. A possible means to control the confound of cuing the perceptual target dimension and cuing taskspecific S-R rules in task switching situations is to assess task preparation when participants switch between two tasks, A and B, that are associated with different perceptual target dimensions, by means of designing another task, C (involving an unrelated S-R mapping), for which it can be argued that its execution would be differentially affected by biasing perceptual processing in favor of the target stimulus dimension of task A or of task B. Administering this probe task after preparation for task A versus after preparation for task B could then be informative about preparatory adjustment of processing task-specific perceptual dimensions. In the current study we applied this method to a task switching paradigm which required switching between tasks associated with selective processing of visual stimulus information presented in a smaller versus in a larger region of space (i.e., the central part of a stimulus configuration versus the whole configuration).

Selective processing of visual stimulus information presented in a particular region of space has been studied extensively under the heading of visuo-spatial attention. An often used method involves the presentation of a target stimulus at a predictable location, surrounded by task-irrelevant distractors (i.e., stimuli that do not include information necessary to solve the task and that may interfere with task performance by being associated with an incorrect response), referred to as flankers (i.e., flanker task, for an overview see Eriksen, 1995). Taking the Flanker Compatibility Effect (FCE), that is, the performance difference between trials involving flankers associated with the same response as the target (henceforth compatible condition) and trials involving flankers associated with a different response than the target (henceforth incompatible condition), as an indicator for the degree of flanker processing, previous research demonstrated attentional focusing on the target location by demonstrating a reduction of the FCE when the spatial distance of target and flankers was increased (e.g., Eriksen and Eriksen, 1974).

Previous research using flanker tasks with variable target locations suggests that preparation time can be used to focus attention on a specific region of space. Such studies found a negative relation of flanker interference and the precision with which the location of the target was cued in advance of the presentation of the imperative stimulus (Eriksen and St. James, 1986). Consistent with these behavioral findings, an fMRI study demonstrated more widely distributed activity in visual cortex

when cuing involved a larger set of possible target locations (Müller N.G. et al., 2003).

A different method of assessing the focusing of attention was introduced by LaBerge (1983). Intermixing trials of a visual search task into blocks of trials involving either a task that implied focal attention (i.e., classifying the central letter of a five-letter word) or a task associated with broader distribution of attention (i.e., classifying the meaning of a five-letter word), this author examined the spatial distribution of attention across the five locations in which the letters were presented. In the search task, a target character could occur at any of these locations with equal probability. Consistent with the assumption that differential attentional sets are adopted in the two types of task blocks, search times displayed a pronounced center-toperiphery gradient across the five locations when the search task was intermixed with trials of the focal attention task, whereas they were hardly affected by the target location when the search task was intermixed with trials of the "defocusing task".

Intermixing a search task as a probe for the distribution of visual attention across a set of locations used for stimulus presentation in a flanker task, Wendt et al. (2012) observed a steeper search time gradient when search task trials were presented in blocks of flanker task trials that were associated with frequent compared to infrequent conflict, suggesting enhanced focusing of visual attention in response to frequent conflict evoked by the flankers. Intermixing search task trials into blocks of trials of a flanker task with asymmetrical stimuli (i.e., two identical copies of the central letter presented on one side and two instances of a different letter on the other side), Wendt et al. (2014a) obtained a steeper search time gradient when instructions asked participants to respond to the central character than to the letter presented three times (which was always identical to the central letter, yielding equivalence of the two task instructions regarding the target-response relation on each trial), suggesting that attention was focused more strongly on the location of the central letter in the former case.

Noteworthy, studies involving the probe task method to assess the attentional set associated with different tasks (LaBerge, 1983), with different frequencies of flanker conflict (Wendt et al., 2012), or with different task instructions (Wendt et al., 2014a) have so far been based on blockwise manipulations of attention, precluding conclusions about trial-to-trial adjustment of visual attention. A recent study by Longman et al. (2013), however, recorded eye movements when participants switched between responding to the photograph of a face or to a letter, superimposed on the face's forehead. Eye fixations on regions relevant for the currently irrelevant task were more frequent in task switch than in task repetition trials, and this difference was reduced when the preparation interval was increased, suggesting both persistence and preparatory adjustment of (overt) attention.

Presenting tasks that differ regarding their demands of visuospatial stimulus selection and intermixing trials of a search task to probe the distribution of visual attention across a region of the visual field seems a promising means to assess, selectively, persistence and preparation of task-specific sets of visual attention, as a particular component of the task-set. In the current study, we applied this methodological approach. Experiment 1 involved a conceptual replication of previous studies that found differential search time patterns consistent with assumptions made regarding attentional sets adopted for different tasks or other context conditions, presented in the majority of trials (LaBerge, 1983; Wendt et al., 2012, 2014a). More specifically, two tasks afforded by the same set of stimuli were alternated between blocks of trials. One of the tasks required responding to the identity of a centrally presented target character and ignoring adjacent stimulus characters that could be identical to or different from the target (i.e., an Eriksen flanker task). By contrast, the other task required judging whether all characters were the same or not. In both task blocks, we intermixed trials of a search task involving a target stimulus that could occur in any of the three possible character locations. Because the context task was kept constant for a block of trials search time patterns may reveal attentional sets adopted in a sustained manner and are not informative regarding (trial-to-trial) dynamics of attentional adjustment in response to (anticipated) changing attentional demands. In Experiment 2, we pursued this issue by examining search time patterns as a function of preparation for each of the other two tasks as well as a function of previous execution thereof.

#### **EXPERIMENT 1**

Vertically arranged strings of three letters served as stimuli for two different tasks. Only the letters H and S were used, and the top and bottom position always involved the same letter. To manipulate stimulus selection demands, an Eriksen flanker task, in which participants identified the centrally presented letter, was contrasted with a Same/Different task, in which participants judged whether all three letters were identical or not. To probe the distribution of visual attention across the three locations at which letters occurred, a visual search task was used. In this task, three digits were presented in the same locations as the letters in the letter tasks. One of these locations, randomly chosen on each trial, contained one of two possible target digits, which participants were instructed to identify. We expected to replicate and extend previous findings of a steeper center-to-periphery gradient of search times in blocks of trials in which the context task was assumed to be associated with stronger attentional focusing on the central location (LaBerge, 1983; Wendt et al., 2012, 2014a).

#### Method

#### **Participants**

Six female and 14 male students of the Helmut Schmidt University/University of the Federal Armed Forces Hamburg, ranging in age from 21 to 29 years, participated in a single-session experiment in exchange for partial fulfillment of course requirements.

#### Apparatus and Stimuli

The experiment took place in a silent, dimly lit room with a 19-inch. LCD monitor with a refresh rate of 60 Hz. Subjects sat approximately 80 cm away from the monitor. Responses were given by pressing one of two response keys which were mounted on an external rectangular keyboard (10 cm  $\times$  18 cm). The

response keys extended 1.0 cm  $\times$  1.0 cm and were separated by 8.0 cm (parallel to the keyboard's long axis). Participants pressed the response keys with the index or middle fingers of their left and right hands (hands uncrossed).

The stimuli were presented in white on a dark gray background, inside a thin white rectangular frame (96 mm  $\times$  102 mm) in the center of the screen. In both the letter tasks and in the search task the stimuli involved three-element-strings, presented in vertical format. In both letter tasks a central capital letter (H or S) was flanked by either two copies of the same or the alternative letter, forming stimuli with same (HHH, SSS) or with different letters (SHS, HSH). Search task stimuli were made up of three different digits drawn from the set of 0-9. Letters and digits extended from 5 to 10 mm horizontally, depending on the precise character, and 12 mm vertically. A three-elementstring subtended approximately 0.72° horizontally and 3.8° vertically. In the Eriksen task, responses to the target letter H and S were mapped to the left and right response key, respectively. In the Same/Different task homogeneous and heterogeneous letter strings were assigned the left and the right response key, respectively. In the search task, the target digits 3 and 7 were mapped to the left and right response key, respectively.

#### **Procedure**

Participants were first administered three practice blocks, involving 40 trials each. The first practice block comprised only trials of the search task. The second practice block comprised trials of the Eriksen task and trials of the search task. The third practice block comprised trials of the Same/Different task and trials of the search task. All constraints of task and stimulus selection were identical to the constraints of the experimental blocks. Subsequently, 12 experimental blocks, of 99 trials each, were started. Blocks involving the Eriksen task and blocks involving the Same/Different task were presented alternately, and the order of presentation was counterbalanced across participants. Search task trials were never presented on consecutive trials. Following a letter task trial (i.e., Eriksen task or Same/Different task, depending on the current block), the probabilities of a search task trial or of another letter task trial were 50%, each. In the letter tasks, the central stimulus element and the peripherally presented stimulus elements (which always matched) were chosen randomly on each trial, yielding 50% probabilities for both a homogenous and a heterogeneous letter string. In the search task, the target digit (i.e., 3 or 7) and the target location (i.e., top, central, and bottom) were randomly chosen. Two additional digits (differing from the possible target digits and from each other) were randomly chosen for the remaining two locations. Participants were instructed to respond as fast as possible while avoiding errors.

After each block, participants received written feedback about their average RT and error rate of the block and were informed about the letter task of the upcoming block. They were given the opportunity for a self-timed pause. Letter and digit stimuli were presented for 150 ms. In case of a correct response the next stimulus appeared after 1300 ms. After an incorrect response

the word "falsch" ("wrong") was presented at the bottom of the stimulus frame for 800 ms. Again, the next stimulus appeared after 1,300 ms. An experimental session took from 50 to 65 min.

#### Results

The first three trials of each block were considered "warm-up" trials and not analyzed. In addition, data from trials following an erroneous response as well as data from trials associated with RTs deviating more than 2.5 standard deviations from the mean RT of each experimental condition per participant were discarded from the statistical analyses.

Although only performance in the search task was of primary interest with regard to the purpose of our study, we also analyzed the response data in the two letter tasks. Specifically, RTs and error percentages were broken down to the factors Task (Eriksen, Same/Different), Homogeneity/Heterogeneity of the letter string, and Congruency between tasks (i.e., whether a given letter string required the same or different responses in the two tasks [i.e., congruent and incongruent, respectively]). (We chose the labels "homogeneous" and "heterogeneous" to refer to the letter strings, rather than the common labels "flanker-compatible" and "flanker-incompatible" because the latter would not seem appropriate for the Same/Different Task, in which the letters presented in peripheral locations do not act as [compatible or incompatible] distractors). Descriptive statistics are presented in Table 1.

Mean RTs and error percentages in the search task are displayed in Figure 1. To analyze performance in the search task, an Analysis of Variance (ANOVA) was conducted on the mean RTs with repeated measures on the factors Target Position (top, center, and bottom) and Context Letter Task (Eriksen, Same/Different). Both the main effects of Context Letter Task and Target Position as well as the two-way-interaction were significant, F(1,19) = 12.3, p < 0.01, MSE = 1,023.1, F(2,38) = 18.5, p < 0.01, MSE = 2,082.0, and F(2,38) = 18.7, p < 0.01, MSE = 1,327.1, respectively. As can be seen in Figure 1, a pronounced center-to-periphery gradient of search times occurred in the Eriksen Task blocks but not in the Same/Different Task blocks. RTs were shortest for centrally presented targets in the Eriksen Task blocks, longest for targets presented in non-central locations in the Eriksen Task blocks, and intermediate for all locations in the Same/Different Task blocks. A corresponding ANOVA on the mean error proportions yielded only a significant main effect of Target Position, F(2,38) = 5.77, p < 0.01, MSE = 0.1298, indicating that fewer errors were made

TABLE 1 | Mean reaction times in ms and error percentages (in parantheses) of the letter task trials in Experiment 1 as a function of Task (Eriksen, Same/Different), Stimulus Type (homogenous, heterogeneous), and Response Congruency between tasks.

	Eri	ksen	Same/D	Different
	Congruent	Incongruent	Congruent	Incongruent
Homogenous	489 (4.1)	494 (4.2)	491 (4.4)	501 (6.1)
Heterogeneous	509 (3.9)	519 (4.9)	536 (3.7)	538 (3.7)

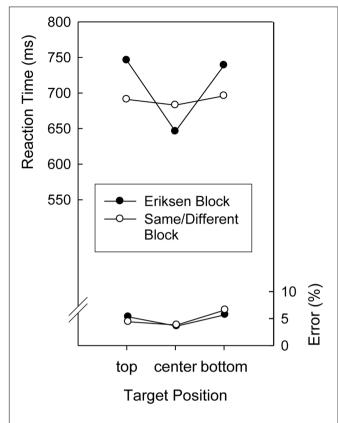


FIGURE 1 | Mean reaction times and error percentages in the search task of Experiment 1 as a function of target position and block (Eriksen, Same/Different).

when the target digit was presented in the central position than when it was presented in peripheral locations (see **Figure 1**)<sup>1</sup>.

#### **Discussion**

The results of Experiment 1 extended previous findings that search time patterns in intermixed trials of a visual search task can be affected by the stimulus selection demands or by attention-relevant stimulus-response contingencies of a context task (e.g., LaBerge, 1983; LaBerge and Brown, 1989; Wendt et al., 2012, 2014a). Specifically, as expected on the assumption that participants adopt a more focused set of visual attention

in blocks of trials including predominantly Eriksen flanker task trials than in blocks of trials including predominantly trials of a task requiring a homogeneous/heterogeneous judgment regarding a target-flanker ensemble, the RT pattern in intermixed trials of a visual search task displayed a more pronounced center-to-periphery gradient in the former case. Although the precise processes underlying the different search time patterns can be debated (see "General Discussion"), we note that it seems difficult to ascribe this finding to other differences between the two letter tasks than their "spatial target regions," such as the task-specific matching operations (i.e., comparing a current stimulus with a memory representation versus with another currently presented stimulus) or the task-specific S-R translation rules. Thus the results of Experiment 1 suggest that the search task employed provides a useful means to assess the set of visual attention associated with a different task that comprises a different set of

Because the search task was intermixed into blocks of trials associated with either the Eriksen flanker task or the Same/Different task, the difference in search time patterns may reflect a sustained form of adoption of task-specific sets of visual attention, kept more or less constant throughout a block of trials. As an alternative, it may result from persistence of a set, used on the direct predecessor trial, or, given that the search task always occurred with lower likelihood than the letter task of the block, from preparatory re-adoption of a rapidly decayed set during the pre-target interval.

#### **EXPERIMENT 2**

In Experiment 2, trial-to-trial persistence and preparation of task-specific attentional sets were investigated by intermixing the Eriksen task and the Same/Different task in the same block of trials and presenting cues that indicated the upcoming task in advance of the imperative stimulus. To assess task-specificity of visual attention, again, search task trials occurred unpredictably, that is, after a letter task cue. Assuming preparatory adoption of the attentional set associated with the cued task we expected a more pronounced center-to-periphery gradient of search times after a cue that indicated the Eriksen task than after a cue that indicated the Same/Different task. Similarly, assuming persistence of the attentional set associated with the letter task executed on the preceding trial we expected a more pronounced center-to-periphery gradient of search times after an Eriksen task trial than after a Same/Different task trial

To control for possible "exogenous" cuing effects (i.e., focusing of attention to the region covered by the cue), the experiment was run in two versions. The procedure of these versions differed only regarding the type of cues used: Version 1 involved written words, presented in the center of the screen, whereas version 2 involved three vertically arranged disks, displayed in a task-specific color, that covered the whole area of a three-letter/digit string.

<sup>&</sup>lt;sup>1</sup>To examine possible effects from the search task on processing of the letter tasks, we conducted an additional analysis, based only on the RT data from letter task trials preceded by a search task trial, including the factors Task (Eriksen, Same/Different), Homogeneity/Heterogeneity of the letter string, Congruency between tasks, and Target position on the preceding trial (central, peripheral). This analysis yielded a significant three-way interaction involving Task, Homogeneity/Heterogeneity of the letter string, and Target position on the preceding trial, F(1,19) = 8.2, p < 0.02, MSE = 4161.8, demonstrating that responding to a heterogeneous letter string in the flanker task was slowed by a preceding search task target presented at a peripheral location whereas no such slowing occurred for homogeneous letter strings. A similar result was observed by Wendt et al. (2012). Consistent with the notion that the slowing observed for heterogeneous letter strings reflected an increase in response competition due to higher deployment of attention to a flanker stimulus (i.e., persistence of attentional orienting of the preceding search task trial), no such slowing occurred in the Same/Different Task for either type of letter string.

#### Method

#### **Participants**

Forty students of the Helmut Schmidt University/University of the Federal Armed Forces Hamburg participated in a single-session experiment in exchange for partial fulfillment of course requirements. None of them had participated in Experiment 1. The word cue version (i.e., Version 1) included 9 female and 11 male participants, ranging in age from 20 to 28 years. The dots cue version (i.e., Version 2) included 3 female and 17 male participants, ranging in age from 20 to 29 years.

#### Apparatus and Stimuli

Identical to Experiment 1, with the exception that each stimulus of the letter tasks and of the search task was preceded by the presentation of a task cue. In Version 1 the cues were the words "Mitte" ("center"), indicating the Eriksen task, and "Gesamt" ("entire"), indicating the Same/Different task. The word "Mitte" extended 25 mm horizontally and 8 mm vertically (about 1.8° × 0.6° of visual angle), and the word "Gesamt" extended 32 mm horizontally and 8 mm vertically (about 2.3° × 0.6° of visual angle). The cues were presented in the center of the screen in white color. In Version 2, the cues were three vertically arranged colored disks presented in the same positions as the letter or digit stimuli. They measured 15 mm in diameter each (around 1.1°, all three  $1.1^{\circ} \times 3.8^{\circ}$ ). The disks were either yellow or cyan. Balanced across participants yellow disks indicated the Eriksen task and cyan-colored disks indicated the Same/Different task or vice versa.

#### **Procedure**

The procedure of Experiment 2 was identical to the procedure of Experiment 1 with the following exceptions. First, each imperative stimulus was preceded by a task cue. The cue was presented 1,300 ms after a response was made to the preceding trial's stimulus and remained on the screen for 800 ms, directly followed by the imperative stimulus. Second, the practice phase involved four blocks of trials. A first practice block comprised only Eriksen task trials, a second practice block comprised only Same/Different task trials, and a third practice block comprised only search task trials. These blocks included 20 trials each. Each trial started with the presentation of a task cue. (For the letter task blocks, the cue was redundant. In the search task block, the cue was chosen randomly from the two letter task cues on each trial). A final practice block of 40 trials involved the presentation of all three tasks with the same constraints of task and stimulus selection that were realized in the following 12 experimental blocks (that comprised 99 trials each). Third, all experimental blocks were structurally identical. They involved the presentation of all three tasks, preceded on each trial by a task cue. Whereas letter task trials were always validly cued (i.e., preceded by their corresponding task cue), on search task trials the cue was chosen randomly from the two possible letter task cues. After a search task trial, the Eriksen task and the Same/Different task occurred with a probability of 50% each. (The search task was never presented on consecutive trials). After a letter task trial the probability

for each of the letter tasks was 4/11 and the probability for the search task was 3/11. An experimental session took from 55 to 65 min.

#### Results

The same routines for data exclusion were applied as in Experiment 1. Descriptive values of the performance in the letter tasks are displayed in **Table 2**.

Performance in the search task was analyzed by conducting ANOVAs with repeated measures on the factors Version (word cues, color cues), Cued Task (Eriksen, Same/Different), Preceding Task (Eriksen, Same/Different), and Target Position (top, center, and bottom), on the mean RTs and on the mean error proportions. Regarding RTs, a main effect of Target Position, F(2,76) = 21.3, p < 0.01, MSE = 5,908.0, indicated a clear center-to-periphery gradient of search times that was modulated by Cued Task, yielding a significant two-way interaction, F(2,76) = 3.9, p < 0.03, MSE = 8,558.8. Figure 2 displays the pattern of search times for the cuing conditions, separately for the two versions of the experiment. A planned comparison that contrasted quadratic trends across the three target positions demonstrated that the center-to-periphery gradient of search times was more pronounced after Eriksen task cues than after Same/Different task cues, F(1,38) = 16.2, p < 0.01, MSE = 2,852.1. This was not modulated by Version, as demonstrated by another planned comparison, F(1,38) < 1.

As can be seen in Figure 2, responses after Eriksen task cues were slower than responses after Same/Different task cues in Version 1 and slightly faster in Version 2, resulting in both a significant main effect of Cued Task, F(1,38) = 6.1, p < 0.02, MSE = 3,321.5, as well as a significant two-way interaction with Version, F(1,38) = 10.9, p < 0.01, MSE = 3,321.5.

Although Target Position did not interact with Preceding Task, F(2,76) < 1, the two-way interaction involving Cued Task and Preceding Task was significant, F(1,38) = 14.8, p < 0.01, MSE = 2,215.8. As can be seen in **Figures 3**, **4**, this was because responding after an Eriksen task cue was faster after Eriksen task trials than after Same/Different Task trials (833 ms versus 845 ms), whereas responding after a Same/Different task cue was faster after Same/Different Task trials than after Eriksen task trials (815 ms versus 836 ms). Finally, all factors entered into a complicated four-way interaction, F(2,76) = 3.4, p < 0.04, MSE = 7,099.7, displayed in Figures 3, 4.

A corresponding ANOVA on the mean error proportions yielded a significant main effect of Version, F(1,38) = 6.4, p < 0.02, MSE = 0.01861, indicating that overall fewer errors were made with color cues (i.e., Version 2, 2.8%) than with word cues (i.e., Version 1, 6.0%). This was modulated by significant two-way interactions with Cued Task and Preceding Task, F(1,38) = 4.4, p < 0.05, MSE = 0.00344, and F(1,38) = 5.5, p < 0.03, MSE = 0.001728, respectively. Responses were more error-prone after Eriksen task cues than after Same/Different task cues in Version 1 (6.8% versus 5.2%), and this was slightly reversed in Version 2 (3.1% versus 2.5%). Also, responses were more errorprone after Eriksen task trials than after Same/Different task trials in Version 1 (6.6% versus 5.4%), and this was slightly reversed in Version 2 (3.1% versus 2.6%).

TABLE 2 | Mean reaction times in ms and error percentages (in parantheses) of the letter task trials in Experiment 2 as a function of Version (1/word cues, 2/color cues), Task (Eriksen, Same/Different), Stimulus Type (homogenous, heterogeneous), and Response Congruency between tasks.

	Version 1 (v	word cues)			Version 2 (co	olor cues)	
Eri	ksen	Same/	Different	Eri	ksen	Same/D	ifferent
Cong	Incong	Cong	Incong	Cong	Incong	Cong	Incong
618 (4.4)	615 (14.0)	554 (4.3)	614 (12.7)	686 (2.2)	748 (10.0)	640 (2.3) 703 (3.4)	712 (7.9) 758 (9.8)
	<b>Cong</b> 618 (4.4)	Eriksen           Cong         Incong           618 (4.4)         615 (14.0)	Cong         Incong         Cong           618 (4.4)         615 (14.0)         554 (4.3)	Eriksen         Same/Different           Cong         Incong         Cong         Incong           618 (4.4)         615 (14.0)         554 (4.3)         614 (12.7)	Eriksen         Same/Different         Eriksen           Cong         Incong         Cong         Incong         Cong           618 (4.4)         615 (14.0)         554 (4.3)         614 (12.7)         686 (2.2)	Eriksen Same/Different Eriksen  Cong Incong Cong Incong Cong Incong	Eriksen         Same/Different         Eriksen         Same/D           Cong         Incong         Cong         Incong         Cong           618 (4.4)         615 (14.0)         554 (4.3)         614 (12.7)         686 (2.2)         748 (10.0)         640 (2.3)

Cong, congruent; incong, incongruent; hom, homogenous; het, heterogeneous.

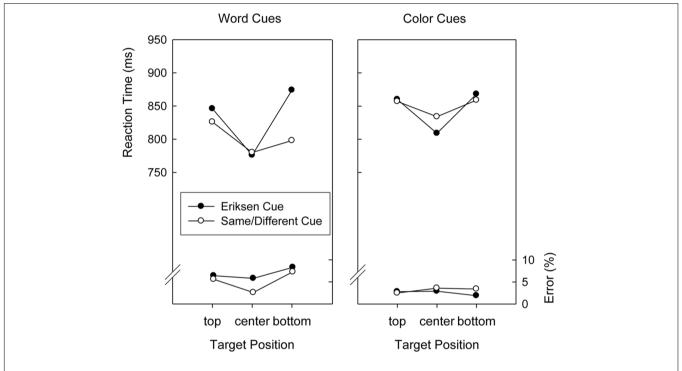


FIGURE 2 | Mean reaction times and error percentages in the search task of Experiment 2 as a function of version (word cues, color cues), cued task, and target position.

The main effect of Target Position was marginally significant, F(2,76) = 2.5, p = 0.08, MSE = 0.00352, and only modulated by Version, F(2,76) = 5.2, p < 0.01, MSE = 0.00352. As can be seen in **Figure 2**, a center-to-periphery gradient of response accuracy occurred when word cues were used but not when color cues were used.

Finally, the two-way interaction of Cued Task and Preceding Task was marginally significant, F(1,38) = 3.4, p = 0.07, MSE = 0.00342, because responding in trials involving an Eriksen task cue was more error-prone after Eriksen task trials than after Same/Different Task trials (5.4% versus 0.4%), whereas responding in trials involving a Same/Different task cue was more error-prone after Same/Different Task trials than after Eriksen task trials (4.5% versus 3.8%).

#### **Discussion**

The most important result of Experiment 2 was that the pattern of search times was affected by the to-be-expected task.

Specifically, a more pronounced center-to-periphery gradient occurred after a cue indicating an Eriksen flanker task, that required the identification of the central element of a three-letter string, than after a cue indicating a Same/Different task, in which homogeneity/heterogeneity of the whole letter string had to be evaluated. This finding was expected on the assumption that participants would adjust their ability to process visual stimulus information to the characteristics of the anticipated task, focusing attention to a particular location or distributing it over a wider area.

The pattern of search task performance was also affected by the type of cue used although this effect was only significant in the error analysis. Specifically, we observed an advantage for targets presented in the central location in Version 1, but not in Version 2, in which color cues were used. This finding may be explained in terms of exogenous cuing of attention by the spatial position and extension of the cue. Unlike the color cues, that covered the area of the complete three-letter/digit strings,

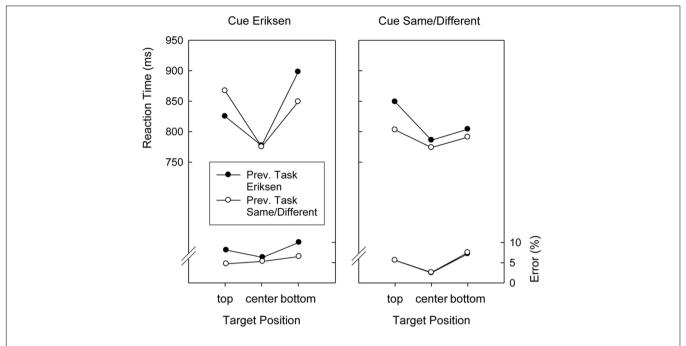


FIGURE 3 | Mean reaction times and error percentages in the search task of Version 1 (word cues) of Experiment 2 as a function of cued task, previous task, and target position.

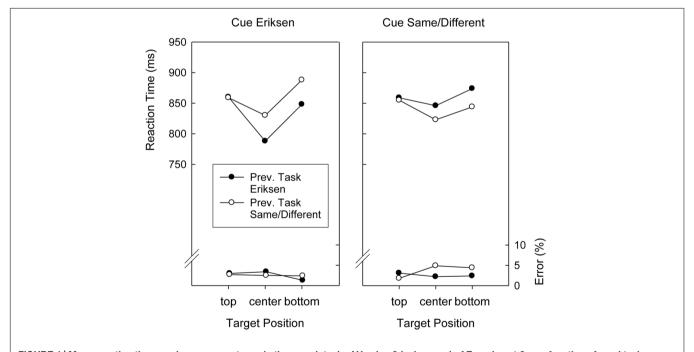


FIGURE 4 | Mean reaction times and error percentages in the search task of Version 2 (color cues) of Experiment 2 as a function of cued task, previous task, and target position.

the words used as cues were presented in the horizontal midline of the screen and corresponded in height to a single digit of the search task. Cue type-induced focusing of attention could not be corroborated, however, in an analysis of the performance patterns in the letter tasks. As can be seen in **Table 2**, there was neither

a relative advantage of the Eriksen task in Version 1 and of the Same/Different task in Version 2, nor a larger FCE (homogenous versus heterogeneous stimuli) in Version 2 than in Version 1. Importantly, irrespective of all possible differences in exogenous cuing of attention, the modulation of the search time gradient by

the indicated task was found with both types of cues used in the experiment.

Contrasting with the cuing effect, the pattern of search task performance across the three target locations was unaffected by the type of task executed on the directly preceding trial. The experiment thus yielded no support for persistence of task-specific sets of visual attention into a subsequent trial, at least if the following trial involves a task associated with a different set of visual attention and the possibility to prepare for it.

Search task performance was, however, overall faster and (marginally significantly) more error-prone after a cue indicating a task repetition than after a cue indicating a task switch. This finding suggests that participants adjusted their response strategy to the expected task sequence (in addition to adjusting their set of visual attention to the expected task). This suggestion is consistent with the results of modeling work. Specifically, Schmitz and Voss (2012, see also Karayanidis et al., 2009), applying a diffusion model to a standard task switching situation, inferred a lower degree of response caution in (prepared) task repetition trials than in task switch trials.

#### **GENERAL DISCUSSION**

Intermixing trials of a probe task, designed to be sensitive to selected aspects of task-specific S-R processing, seems an efficient method to investigate persistence and preparation of specific components of task-sets. The current study aimed primarily at pursuing the set of visual attention but also yielded preliminary evidence regarding response caution. Consistent with previous results of steeper search time gradients when context conditions were arguably associated with stronger focusing of attention, Experiment 1 yielded a corresponding search time pattern when the search task was intermixed into blocks of trials of the Eriksen flanker task versus into blocks of trials of the Same/Different task, suggesting task-specific focusing or defocusing of visuo-spatial attention. The blockwise manipulation, however, precludes interpreting these results in terms of dynamic trial-to-trial adjustment.

Experiment 2 demonstrated preparation-based adoption of task-specific sets of visual attention by yielding differentially steep search time gradients after (invalid) cuing of the two letter tasks. By contrast there was no indication of a difference in search time gradients as a function of the type of the directly preceding letter task. Regarding the letter tasks, the situation created in Experiment 2 resembles typical task switching studies in which the same stimuli are administered under varying S-R mappings that have to be applied to perceptually different stimulus dimensions, such as shape and color. Although task-specific perceptual biasing during preparation has been assumed in some models of task switching (e.g., Meiran, 2000) we know of no evidence for this assertion that is comparable to the results of Experiment 2 of the current study.

Further research is needed to clarify several questions left open by the current findings. First, the lack of an influence of the attentional demands of the preceding task on the search time pattern deserves further analysis. At the current stage we can only speculate whether this reflects passive decay or inhibition of a previous attentional set or overwriting by preparation for the upcoming one. Manipulations of the length of the inter-trial interval and of the certainty regarding the identity of the upcoming task may be helpful to decide among these possibilities. Second, although the preparation effect found in the current study seems consistent with an early, sensoryperceptual locus, it may also be brought about by re-adjustment of processing weights assigned to stimulus information extracted from central and peripheral locations during a later, postperceptual processing phase. Distinguishing between these possibilities on the basis of purely behavioral findings may be difficult. Complimentary analysis of physiological measures reflecting early processing stages of stimuli presented in the different locations seem a viable option to shed light on this issue (see, Wendt et al., 2014b; Jost et al., 2017, for application of a similar method concerning the question of adjustment of processing of distractors presented in advance of the target). Third, as noted in the "Introduction," Longman et al. (2013) observed an effect of preparation on eye fixations in regions of relevance for the two tasks between which participants switched, suggesting that overt attentional selection is prepared when switching between tasks. Although situations in which stimulus information relevant for the two tasks is presented in different locations seem particularly likely (and actually necessary, given a critical distance between these locations is exceeded) to be associated with task-specific sets of overt attentional selection (i.e., different fixation points), presenting critical information in a smaller region of space in one task than in the other may also invoke functional differences in eye movements or fixation patterns. Because we did not control eye movements, it can thus not be dismissed that the preparation effect was brought about by overt rather than covert attentional focusing.

Potentially limiting the scope of our findings it should be pointed out that switching between tasks which require differential degrees of focusing of visuo-spatial attention, as done in the current study, seems particularly well-suited for investigations based on intermixing a probe task because clear predictions can be made regarding RT patterns (i.e., steeper search time gradient in the context of a task that requires stronger focusing). Generalization of such findings to more typical task switching situations, such as switching between color and shape classifications, seems premature, however. Given the promising results of the current study, however, substantial progress regarding the questions of persistence and preparation of processing task-specific perceptual dimensions, in general, may be made if appropriate probe tasks can be developed for other kinds of stimulus dimensions than the size of the spatial region containing critical stimulus information. An obvious problem inherent in this approach relates to the possibility of changed task processing strategies resulting from intermixing probe task trials. For instance, regarding the current study, administering a proportion of trials in which peripherally presented stimuli bear task relevance may lead participants to adopt a less focused strategy in the Eriksen task as they would do in single-task Eriksen blocks. Constituting an example of a very reactive measurement, progress obtained with more sophisticated probe task procedures should thus depend on a more profound understanding of the adjustment of task processing strategies to contextual factors.

Although we had no *a priori* hypothesis regarding preparatory adjustment of response strategies, the speed-accuracy tradeoff found in search task trials that were cued as (letter) task repetitions versus switches provides striking evidence for the notion of a lowering of the response criterion in anticipation of a task repetition, derived from modeling work (Karayanidis et al., 2009; Schmitz and Voss, 2012). Intriguingly, evidence for this suggestion in the form of a speed-accuracy trade-off between well prepared task repetitions and switches seems widely missing. This would not seem surprising given that prepared task repetitions should be particularly easy to perform, thus providing little room for erroneous responding even if response caution is reduced. The probe task method used in the current study might be advantageous in this regard because it compares performance after preparation for a task repetition and for a task switch in an unexpected task which should not benefit from the facilitation one would expect to see in the prepared task repetition, thus increasing error likelihood.

From a methodological point of view, intermixing probe task trials may thus be useful to identify several different task-set components that are affected by preparation. The current study provides clear evidence for preparatory adoption of task-specific sets of visual attention as well as a corroboration of suggestions of task sequence-specific preparation of the response strategy.

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#### **ETHICS STATEMENT**

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study. Ethical review and approval was not required for this study in accordance with the national and institutional requirements.

#### **AUTHOR CONTRIBUTIONS**

MW, AL-R, and TJ planned the experiments. AL-R programmed the experimental software. SK collected the data. MW and AL-R analyzed the data. All authors wrote the article

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**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Age Differences in the Transfer and Maintenance of Practice-Induced Improvements in Task Switching: The Impact of Working-Memory and Inhibition Demands

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Recent aging studies on training in task switching found that older adults showed larger improvements to an untrained switching task as younger adults do. However, less clear is what type of cognitive control processes can explain these training gains as participants were trained with a particular type of switching task including bivalent stimuli, requiring high inhibition demands, and no task cues helping them keeping track of the task sequence, and by this, requiring high working-memory (WM) demands. The aims of this study were first to specify whether inhibition, WM, or switching demands are critical for the occurrence of transfer and whether this transfer depends on the degree of overlap between training and transfer situation; and second to assess whether practiced-induced gains in task switching can be maintained over a longer period of time. To this end, we created five training conditions that varied in switching (switching vs. single task training), inhibition (switching training with bivalent or univalent stimuli), and WM demands (switching training with or without task cues). We investigated 81 younger adults and 82 older adults with a pretest-training-posttest design and a followup measurement after 6 months. Results indicated that all training and age groups showed improvements in task switching and a differential effect of training condition on improvements to an untrained switching task in younger and older adults. For younger adults, we found larger improvements in task switching for the switching groups than the single-task training group independently of inhibition and WM demands, suggesting that practice in switching is most critical. However, these benefits disappeared after 6 months. In contrast, for older adults training groups practicing task switching under high inhibition demands showed larger improvements to untrained switching tasks than the other groups. Moreover, these benefits were maintained over time. We also found that the transfer of benefits in task switching was larger with greater overlap between training and transfer situation. However, results revealed no evidence for transfer to other untrained cognitive task. Overall, the findings suggest that training in resolving interference while switching between two tasks is most critical for the occurrence of transfer in the elderly.

Keywords: task-switching training, transfer, aging, working memory, inhibition

#### INTRODUCTION

During the last century, life expectancy has increased and this trend is expected to continue in the future (Vaupel, 2010). As a consequence, the relative proportion of individuals above 60 years of age will dramatically increase in the next decades. At the same time it is well documented that aging is associated with substantial decline in many areas of cognitive functioning (for recent reviews, Nyberg et al., 2012; Hartshorne and Germine, 2015). However, the ability to improve cognitive functioning remains considerably intact throughout the adult lifespan (for reviews, Lövdén et al., 2010; Lindenberger, 2014). Therefore, one important challenge for aging researchers is to identify whether and how decline in cognitive functioning can be prevented, maintained, or even reversed through effective training interventions (e.g., Mayr, 2008; Kühn and Lindenberger, 2016). An effective training intervention should not only show that (a) the trained ability can be improved after the intervention, but also determine the extent to which these training gains (b) generalize to other domains of functioning and (c) can be maintained over a longer period of time, and finally (d) what training conditions are the best to promote cognitive plasticity for specific age ranges (e.g., Karbach and Kray, 2009; Kray and Ferdinand, 2014). In this study, we examined all four aspects in order to replicate and extend previous findings on the effectiveness of training in task switching in groups of younger and older adults (cf. Karbach and Kray, 2009). In particular, we aimed at investigating the impact of working-memory (WM) and inhibition demands on practice-related improvements in task switching and their effects on the generalizability to similar and dissimilar cognitive control tasks and on the maintenance over half a year compared to initial task performance.

In our previous training study by Karbach and Kray (2009) we used a task-switching training in order to enhance cognitive control abilities. In this type of training, participants had to switch regularly between two task sets, such as categorizing pictures according to colors (task A) or shapes (task B). Cognitive control is indexed by two types of task-switching costs - here termed mixing and switching costs. Mixing costs are defined as the difference in performance between single-task blocks and mixed-task blocks, whereas switching costs are measured as the difference in performance between switch and non-switch trials within mixed-task blocks (cf. Kray and Lindenberger, 2000). Previous research indicated that age differences are much larger in mixing than in switching costs (for a meta-analysis, see Wasylyshyn et al., 2011) and that age differences in mixing costs are maximized in the absence of task cues and under high ambiguity (for a review, see Kray and Ferdinand, 2014). Therefore, Karbach and Kray (2009) used a particular variant of the task-switching paradigm namely the so-called alternatingruns task-switching (AR-TS) paradigm (for reviews, see Kiesel et al., 2010; Grange and Houghton, 2014). Here participants are instructed to alternate between two tasks within a block, according to a predefined sequence, such as to switch the task on every second trial. Hence, no task cue indicated the next to be performed tasks and participants needed to keep track of the task sequence throughout a block. Furthermore, all stimuli were bivalent (or ambiguous) meaning that all stimuli consisted of features relevant for each of the two tasks and responses of both tasks were partly mapped onto the same response button (cf. Rogers and Monsell, 1995). In order to identify optimal training conditions for different age ranges (i.e., children, younger, and older adults) we compared four different training groups: The active control group only performed the single tasks A or B, while the four treatment groups only performed the alternating-run blocks (task-switching training). The first treatment group only practiced the switching between two tasks; the second treatment group practiced task switching and in addition verbalized the next to be performed task, as verbalization has been found to reduce age differences in mixing costs (cf. Kray et al., 2008). Finally, the third treatment group also practiced task switching with verbalization but received a new set of stimuli in each of the practice sessions, inducing variability during the training that in particular has been found to promote transfer of training (cf. Kramer et al., 1995; Green and Bavelier, 2008).

To examine age differences in the transfer of the taskswitching training participants performed untrained but structurally similar switching tasks (referred to as near transfer) and a comprehensive cognitive test battery including two or three indicator tests measuring verbal and visual working memory, inhibition, and fluid intelligence. The results of this training study indicated (a) training-related improvements in task switching in all three age groups; (b) a reduction of mixing and switching costs from pre- to post-test, that is, near transfer gains to a similar switching task that were even more pronounced for children and older adults; (c) and performance improvements in inhibition, working memory, and fluid intelligence in all age groups, suggesting relatively broad far transfer of the switching training (see, Karbach and Kray, 2009). One explanation for this broad transfer effect is that a specific variant of the taskswitching paradigm was applied that involved not only practice in switching processes per se but also WM processes as subjects had to keep track of the task sequence and inhibition processes as they practiced with bivalent (ambiguous) stimuli.

In the meanwhile transfer effects of task-switching training have been proven also in other studies including samples of adolescents (Zinke et al., 2012) and young adults (Pereg et al., 2013; von Bastian and Oberauer, 2013). For instance, Zinke et al. (2012) used a similar task-switching training protocol although with less training sessions (three instead of four) and replicated a reduction of mixing but not of switching costs from pre- to post-test while far transfer effects were only found for WM updating (2-back task) and speed of processing (choice RT task). Pereg et al. (2013) used one training condition of the original Karbach and Kray (2009) study (training in task switching + verbalization + variability) and specifically tested whether this type of switching training transferred to other switching situations (cued task switching and switching after every third trial) as well as to other cognitive tasks including memory, inhibition, and choice RT tasks. Their results indicated practice-induced improvements during the training sessions as well as a larger reduction in mixing and switching costs (but only for a perceptual and not for a semantic switching task) but found no transfer to other switching situations or other cognitive variables (far transfer). Finally, the training study of von Bastian and Oberauer (2013) included the same stimuli as Karbach and Kray (2009), but used a cue-based task-switching training. They found practice-related improvements in task switching as well as near transfer to an AR-TS paradigm with bivalent stimuli, and moreover training-related improvements were correlated with near transfer gains in task switching. However, they found no evidence for far transfer to reasoning, inhibition, or working

In sum, while most studies found evidence for near transfer effects the evidence for far transfer of training in task switching is mixed and less convincing, and may only occur under specific conditions that induce high demands on cognitive control and practice several executive processes at the same time, as in the original Karbach and Kray (2009) study. Indirect evidence for this view comes from a recent dual-task study by Anguera et al. (2013). In their study, they measured multitasking abilities in participants aged 20 to 79 years in a three dimensional video game and found a linear decline in dual-task performance with aging. However, older adults (60-85 years) were trained in an adaptive version of this video game for a period of 1 month. After 12 sessions of practice they showed marked improvements (compared to an active- and a no-contact control group) in multitasking performance, reaching better performance than untrained 20-year-olds. Furthermore, this improvement in multitasking was still observable after 6 months. The training also led to improvements in untrained cognitive abilities, such as enhanced sustained attention and working memory. On the basis of these findings they proposed that training in resolving interference between two tasks that occurs in dual-task like situations is most critical in order to obtain broader transfer of training in older adults.

Considering the recent empirical evidence, it seems that variations in the type of training condition are critical for promoting broader transfer to other cognitive abilities in older adults but maybe also in younger adults. Given that in our previous training study several components of cognitive control were practiced (as participants had to switch between tasks without task cues that help to maintain the task sequence and with ambiguous stimuli that require to inhibit the currently irrelevant task feature), we aimed at determining which of these control components is more critical for inducing transfer of training. To disentangle the relative involvement of switching, inhibition, and WM demands in our training, we created five different training conditions, four switching training conditions (see Figure 1) and one single-task training condition. First, to determine the impact of the switching component we compared the four switching groups against the single-task training group that performed the two tasks always in separate blocks throughout the training sessions. However, note that the single task group served as active control group for the switching groups but also received ambiguous stimuli and no task cues (as they were redundant). Hence, participants in this group also practiced resolving interference but not in a dual-task/switching context. We decided to include this control condition also for reasons of comparability to our first training study. Second, WM demands were manipulated by the presence or absence of task cues (see

Figure 1). Hence, two of the switching training groups received a task cue that helped them to keep track of the task sequence (low WM demands), while the other two groups received no task cues and had to switch the task on every second trial (high WM demands). Furthermore, inhibition demands were manipulated by switching conditions in which either bivalent (ambiguous) or univalent (unambiguous) stimuli were present (see Figure 1). Hence, two of the switching training groups performed the task with bivalent stimuli in which the currently irrelevant task feature had to be suppressed all the time (high inhibition demands), while the other two switching training groups performed the task with univalent stimuli in which the task-relevant stimulus was combined with a neutral feature so that the stimuli directly activated the relevant task (low inhibition demands).

To examine near transfer effects and its maintenance compared to pretest performance the different switching conditions were measured in each training group at pretest, posttest, and after a 6-months follow-up measurement. Far transfer effects were measured by including cognitive tasks measuring working memory, inhibition, and context updating with several indicator tests (for details, see Materials and Methods section).

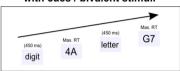
There is now evidence from a variety of studies that mixing and switching costs are substantially reduced with increasing practice in younger as well as in older adults under different type of switching conditions (for reviews, see Kray and Ferdinand, 2014). Furthermore, researchers also found that task-switching costs and age differences therein vary with the amount of task interference and memory load (Mayr, 2001). Age-related differences in task switching were more pronounced in the presence of task ambiguity (Mayr, 2001) and in the absence of task cues (Kray et al., 2002). On the basis of these finding we expected that (a) younger and older adults will show a reduction of switching costs across the four practice sessions; (b) switching costs will be larger in training conditions with high inhibition demands (with bivalent stimuli) than with low inhibition demands (with univalent stimuli); and (c) switching costs will be larger in the training conditions with high memory demands (no task cues) than with low memory demands (with task cues). We had no specific expectations about age and group differences in task-switching improvements across the four training conditions. However, most important here is to show that all groups will show switching improvements during the training session.

On the basis of our previous study, we expected near transfer of training in task switching, that is, larger performance improvements in the training groups compared to the active control group (see Karbach and Kray, 2016). However, less clear is whether the transfer of training is specifically related to the switching, working memory, or inhibition processes that differ between different variants of switching tasks. Hence, if the switching component contributes to the transfer in task switching we expect larger transfer in all training groups compared to the active control group. If the inhibition component is critical we expect larger transfer effects for the training groups that practiced with bivalent stimuli, and finally if the WM component is most critical we expect larger transfer for the groups that

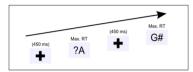
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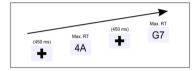
#### with cues / bivalent stimuli



#### without cues / univalent stimuli



#### without cues / bivalent stimuli



 $\textbf{FIGURE 1} \ | \ \textbf{Illustration of the trial procedure, task cues, and stimuli in the four training sessions for the four task-switching training groups.} \\$ 

Participants had to switch between a digit task (odd or even?) and a letter task (consonant or vowel?). Task-switching Training Group 1 received task cues and practiced with univalent stimuli (**Upper/left**). Task-switching Training Group 2 also received task cues and practiced with bivalent stimuli (**Lower/left**). Task-switching Training Group 3 practiced without task cues and with univalent stimuli (**Upper/right**). Task-switching Training Group 4 practiced without task cues and with bivalent stimuli (**Lower/right**).

practiced without task cues. So far there exists less evidence for the maintenance of practice-induced improvements of task switching over a longer period of time. As training in working memory has been shown to maintain up to 6 months and longer in younger as well as in older adults (e.g., Li et al., 2008), we also expected that, if transfer effects can be observed, they persist over time.

As some researchers claimed that the training of task switching is rather specific to the trained situation (e.g., Pereg et al., 2013) the present study allows us to directly test this by assessing whether performance improvements within each of the four task-switching groups only occurs if training and transfer tasks strongly overlap in their cognitive control demands. If not, we should find transfer effects (performance gains) also in switching tasks that only partly overlap with the training task, that is, either overlap in memory or inhibition demands as those experienced at training.

In order to examine differential effects on far transfer measures we included a comprehensive cognitive test battery including indicator tests of WM span and updating, inhibition and fluid intelligence. On the basis of our previous findings (cf. Karbach and Kray, 2009) we expected to find relatively broad transfer to these measures for groups that practice all cognitive control components (switching, working memory, and inhibition), that is, for the task-switching training group that practiced the task without task cues and bivalent stimuli. We also expected that the task-switching groups that practice under higher inhibition demands may show larger transfer on inhibition measures and that the groups that practice with higher WM demands will show larger transfer on WM measures. We had no specific expectations about age differences in these effects.

#### **MATERIALS AND METHODS**

#### **Participants**

Overall 176 participants participated for this study. All participants gave informed written consent in accordance with

the protocols approved by Saarland University. They were recruited from a subject pool at Saarland University and were paid around 60 Euros to participate in the six sessions of the study, plus 20 Euros for a follow-up assessment. The study and applied methods were also approved by the local ethics committee of Saarland University. Thirteen participants had to be excluded from the analysis either because they did not want to finish the study (n = 9), because of health problems (n = 3)or because of technical problems (n = 1). The final sample consisted of 81 younger adults (mean age = 21.9 years; age range = 19-25 years; 49% female; Group 1: n = 16; Group 2: n = 16; Group 3: n = 16; Group 4: n = 17; Group 5: n = 16; see also **Table 1** and Section "Training Intervention: Training Tasks and Groups" for the description of the five groups) and 82 older adults (mean age = 70.8 years; age range = 65-85 years; 52% female; Group 1: n = 17; Group 2: n = 17; Group 3: n = 16; Group 4: n = 16; Group 5: n = 16). For the 6-months follow-up session 71 of the younger age group and 74 of the older adults were willing to return to the lab. Younger and older adults did not significantly differ in years of education (p = 0.11). Comprehensive information about the level of cognitive functioning is provided in the analysis of pretest performance (see Results section and Table 1).

#### **Procedure**

Practice and transfer effects of the task-switching training were assessed by means of a pretest-training-posttest follow-up design. Before practice, all participants completed a pretest assessment to measure baseline performance in several cognitive tasks that lasted about 2.5 to 3 h. During pretest, all participants first gave informed consent before they filled out a demographic questionnaire. Then, we measured baseline performance in the single tasks and four different switching conditions (see Table 1) before subjects received a comprehensive cognitive test battery. The four training sessions were identical in structure and intensity with the previous task-switching

TABLE 1 | Means (M) and standard deviations (SD) as well as *F*- and *p*-values for training group comparisons for all pretest measures separately for the training groups and age groups.

			Training group				
	Group 1 single task – bivalent stimuli	Group 2 with cue – univalent stimuli	Group 3 with cue – bivalent stimuli	Group 4 without cue – univalent stimuli	Group 5 without cue – bivalent stimuli		
Age group	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	F-value	p-value
Mixing costs	(ms)						
Younger	125 (96)	118 (98)	113 (80)	135 (137)	122 (76)	0.12	0.98
Older	282 (128)	272 (144)	271 (140)	278 (149)	268 (119)	0.03	0.99
Switching co	sts (ms)						
Younger	79 (53)	77 (63)	87 (53)	93 (61)	97 (57)	0.37	0.83
Older	96 (106)	106 (108)	95 (59)	108 (65)	100 (84)	0.80	0.99
Counting spa	ın (% correct items)						
Younger	82 (9)	82 (14)	81 (13)	82 (11)	78 (12)	0.44	0.79
Older	76 (15)	72 (12)	77 (17)	74 (13)	69 (11)	1.03	0.40
Reading spar	n (% correct items)						
Younger	81 (10)	76 (14)	78 (13)	76 (18)	76 (15)	0.23	0.92
Older	74 (14)	73 (15)	73 (14)	77 (12)	72 (16)	0.55	0.70
Digit backwa	rd (% correct items)						
Younger	36 (9)	36 (7)	36 (11)	35 (11)	36 (8)	0.18	0.95
Older	30 (7)	25 (12)	26 (8)	22 (9)	29 (12)	1.34	0.26
2-back (prop	ortion of hits minus fal	lse alarms)					
Younger	0.50 (0.3)	0.45 (0.33)	0.41 (0.3)	0.41 (0.3)	0.58 (0.2)	0.79	0.54
Older	0.41 (0.3)	0.45 (0.3)	0.40 (0.3)	0.46 (0.3)	0.46 (0.3)	0.32	0.86
Color-Stroop	Interference (ms)						
Younger	38 (46)	27 (57)	13 (51)	37 (32)	27 (52)	0.71	0.59
Older	121 (68)	86 (67)	72 (40)	112 (140)	111 (93)	0.72	0.59
Number-Stro	op Interference (ms)						
Younger	13 (31)	21 (44)	36 (29)	11 (37)	27 (33)	1.27	0.29
Older	6 (64)	33 (57)	4 (43)	31 (46)	48 (64)	1.46	0.22
AX-CPT Inter	ference (ms)						
Younger	75 (63)	80 (76)	141 (101)	120 (73)	125 (108)	1.84	0.13
Older	123 (117)	132 (123)	114 (100)	129 (177)	96 (251)	0.13	0.97
Raven (numb	er correct items)						
Younger	11 (2.43)	11 (3.19)	11 (2.16)	12 (2.37)	12 (2.66)	0.37	0.83
Older	5.3 (2.32)	5.3 (2.22)	5.3 (2.26)	4.7 (2.68)	4.9 (2.55)	0.19	0.94

training study (Karbach and Kray, 2009). Each training session lasted between 30 and 40 min. Testing time was shorter as compared to this previous study although participants received the same number of trials, but we shortened the preparation time on each trial in the present study. To examine transfer of the task-switching training, participants were assessed with similar type of cognitive tests and questionnaires, except the demographic questionnaire, but in contrast to the previous training study we applied parallel versions of each test and questionnaire in the posttest and follow-up sessions.

The time between pretest and posttest was not significantly different across the five training groups (M=22 days; SD=5.83), neither in the younger age group, p=0.42, nor in the older age group, p=0.14. Training sessions were restricted to be twice weekly. The time between the posttest and the follow-up

session was on average 200 days (SD = 48.79), and again did not significantly differ between the training groups in neither of the two age groups (p = 0.41, p = 0.78, respectively).

## Measures at Pretest, Posttest, and Follow-up

#### Measurement of Near Transfer

In order to measure near transfer of task switching we assessed the baseline performance in the five different switching conditions (described above) with untrained tasks that were structurally quite similar to the training tasks. That means, the structure of tasks, the trial procedure, and block design was identical to the training conditions. We also used combinations of digits and letters but this time subjects had to perform two different tasks. In the "digit" task (Task A) participants were to decide whether the value is smaller (1, 2, 3, 4) or larger (6, 7, 8,

9) than five, and in the "letter" task (Task B) participants were to indicate whether letters were printed either in lowercase (f, t, d, j) or in uppercase (F, T, D, J).

All participants started with two practice blocks, each consisting of nine trials, in which participants performed task A or task B to make sure that they have understood the task instructions. Then, they performed six single-task blocks of task A and task B, each consisting of 17 trials. Thereafter, they performed 12 mixed-task blocks. Hence, participants performed three blocks of each of the four different switching conditions (see Figure 1) that were given in a constant order across subjects at each of the three measurement points: mixed blocks with cues and univalent stimuli; mixed blocks with cues and bivalent stimuli; mixed blocks without cues and univalent stimuli; and mixed blocks without cues and bivalent stimuli. Stimulus presentation was randomly selected in at each measurement time. Mixing costs were defined as the difference in performance between mixed-task blocks and single-task blocks. Switching costs were defined as difference in performance between switch trials and non-switch trials within mixed-task blocks.

#### Measurement of Far Transfer

The cognitive test battery included two or three tests and tasks of four different constructs: (1) Verbal WM was assessed by the Digit Backward, Reading Span, and Counting Span tests; (2) WM updating by the 2-back, 3-back; and (3) inhibition by the Color and Number Stroop tests and the AX-CPT (AX-Continuous Performance Task) test, and (4) fluid intelligence by Raven's Progressive Matrices tests. In addition, as a control variable, processing speed was measured by the Digit-Symbol Substitution test. The cognitive battery included partly similar tasks and tests that have been used in a previous study (Karbach and Kray, 2009), but also new tests. Importantly, in this study were used parallel test versions of each span tasks and fluid intelligences tests, in contrast to previous training studies. For the experimental tasks we used the identical stimuli but randomly created new item lists for each measurement time.

In the *Digit Backward test* the experimenter read aloud a list of numbers of varying length (range = 2–14 items) and the participants had to repeat the numbers of each list in reverse order (adapted from Wechsler, 1981). Four lists of each length were given. The test score was the number of totally correct recalled numbers in each list. The parallel versions for the posttest and the follow-up measurements were identical except that other numbers were randomly assigned to each list.

The Reading and Counting Span tests were originally constructed by Kane et al. (2004), but shortened with 8 trials instead of 12 trials (cf. Karbach and Kray, 2009). The test score in each task version was the number of totally correct items. For the parallel measurements were created new item lists while the structure remained identical.

The 2-back and 3-back tasks (adapted from McElree, 2001) was applied in which participants saw a numbers (ranging from 1 to 9) successively presented for 1000 ms. The task was to monitor the numbers and press a button if the given number was the same as two or three before, respectively, or another button in the other case. The task started with a practice block of 20 trials followed by

the experimental block of 108 trials. The test score was hits minus false alarms. For the older participants an extra practice block was included with a longer stimulus presentation time of 2000 ms. to make them better familiar with the task. However, as the 3-back turned out to be too difficult for older adults they only received the 2-back task.

The Color and Number Stroop tasks were adapted from Salthouse and Meinz (1995). In the color version participants were presented words (e.g., 'red', 'hat') in different colors (red, blue, green, yellow). The task was to indicate the color in which the word was written. In the number version participants were presented characters (e.g., '3', 'M') that varied in the number of the same character ranging from 1 to 4 (e.g., 3, 33, 333, 3333). Responses in both versions were given manual by pressing the left and right index and middle finger. The stimulus-response assignment was constant across participants. The task of the participants was to indicate how many characters were displayed on the screen. Interference effect was defined by subtracting mean reaction times of incongruent trials (e.g., 'red' in blue color; '3') from the mean reaction times of neutral trials (e.g., 'hat'; 'M'). Parallel test versions were structurally identical but different in the item lists across the measurement times.

A modified AX – Continuous Performance Test (i.e., AX-CPT, adapted from Servan-Schreiber et al., 1996) was used to measure interference control. Participants first saw a cue (A, F, G, S) for 500 ms that was followed by a probe (X, C, M, U) for 500 ms. The probe was present until the response was given with a maximum response deadline of 1300 ms. The cue-probe interval was 2000 ms. The task was to press the right response key for an AX cue-probe combination (the frequency of which were 70% of all trials), and the left response key for each other cue-probe combination (that is: AY, BX, BY; the frequency for each type were 10%). As AY and BX trials overlapped with one element of the target pair (AX), either the cue or the probe, these trials induce interference as compared to AX and BY trials (cf. Paxton et al., 2006). Hence, we defined interference costs as the difference in mean performance between interference and non-interference trials

As reasoning tests we applied the Raven's Standard Progressive Matrices (for details, see Raven, 1988). The task of the participants was to find out which figure would fit best a pattern of figures from a given array. The test score was the sum of correctly solved items within 10 min. Parallel test versions were structurally identical but different in the items lists across the measurement times.

#### Training Intervention: Training Tasks and Groups

Participants of all groups were instructed to perform two tasks during the four practice sessions. As stimuli and tasks we used the original Rogers and Monsell (1995) materials in order to manipulate the amount of stimulus-induced interference namely digit-letter combinations (e.g., A4). In the one task, the *digit task* they pressed a left response key if the digit was odd (i.e., 1, 3, 5, 7) and the right response key if the digit was even (i.e., 1, 3, 5, 7). In the second task, the *letter task* they pressed the left key if the letter was consonant (i.e., G, K, M, R) and the right key if the letter was a vowel (i.e., A, E, U, I). The response assignment remained

constant across the practice sessions and individuals. Small signs over the response keys helped the participants to remember the response assignments.

Training sessions for all groups consisted of 24 experimental blocks (17 trials per block), so that all participants received 1632 training trials. Mixed blocks for the task-switching groups were designed in a way that participants received an equal number of trial types (switch and non-switch), task types (A and B), and response types (left and right) and single-task blocks consisted of an equal number of task types and response types. Trials started with a cue or fixation cross that remained for 1000 ms, which was followed by the target that remained on the screen until the subject responded. The time interval between the response and the next trial was fixed to a 25 ms blank screen (see **Figure 1**). Participants were instructed to respond as fast and as accurate as possible. Feedback about their performance (error rate, RT) was given at the end of each block.

Before the training sessions, participants were assigned to one of five training groups based on their pretest performance in task switching (median RTs for single tasks and mixing costs, perceptual speed of processing, and number of correct answers), performance in the Stroop (median RT for interference costs for the color and the number task), WM span tasks (% correct answers), Updating tasks (PR scores and median RT on the AX-CPT), and the Raven score (number of correct answers). After pretest we calculated all test scores for each participant. For each age group, the first five participants were assigned randomly to the five different training groups. Then we calculated standard deviations separately for all test scores of these five participants. The sum of standard deviations served as an indicator of how similar or different these five groups were to each other. For each next participant, we tested how the indicator would change for the five potential assignments. We then selected the group for which the changing indicator score was lowest.

The training groups differed regarding the switching demands (performing single tasks versus performing mixed-task blocks), WM demands (performing mixed-task blocks with task cue versus no task cue), and inhibition demands (mixing blocks consisting of bivalent versus univalent stimuli) as described in more detail in the following (see also **Figure 1**).

Single-task Training Group (active control group). In this group participants performed the letter and digit task in separate blocks (i.e., single-task blocks) that were grouped together. In each of the four practice sessions they either first practiced the letter task and then the digit task, and vice versa in the next practice session. All stimuli were bivalent, that is, participants received only digit-letter combinations (i.e., A4, 2G; U7, etc.) throughout the practice sessions. Note that this condition was similar to our previous active control group condition (Karbach and Kray, 2009) except that we used other stimulus materials (pictures instead of letter-number combinations).

Task-switching Training Group 1 (low WM and low inhibition demands). Like all other task-switching training groups, participants in this group received only mixed-task blocks and were instructed to switch the task on every second trial. Demands on keeping track of the task sequence were low in this group, as

they received additional task cues on each trial, either the word "letter" or "digit," indicating the next task. Also, demands on interference control were low as all stimuli were univalent, that is, the digit or letter stimuli were combined with task-irrelevant (neutral) features (i.e., [\*, ?, #, %]; see also **Figure 1**).

Task-switching Training Group 2 (low WM and high inhibition demands). Like the task-switching training group 1, participants alternated between the two tasks and received task cues in order to keep track of the task sequence. Interference demands were higher as compared to the first task-switching training group as they only received bivalent stimuli throughout the practice sessions (see Figure 1).

Task-switching Training Group 3 (high WM and low inhibition demands). Like task-switching training group 1, participants alternated between the two tasks and received only univalent stimuli. In contrast to group 1, they received no additional task cues that helped them to keep track of the task sequence. Instead they only saw a fixation cross at the beginning of each trial (see Figure 1).

Task-switching Group 4 (high WM and high inhibition demands). This training group comes closest to one of our training groups of the previous study (Karbach and Kray, 2009) in which participants had to switch between the two tasks without receiving task cues while task interference was high due to bivalent stimuli.

#### Data Analysis

For the task-switching data the first trials of each block were discarded during analysis, as well as responses slower than three standard deviations from the mean of each experimental condition. For all analyses IBM SPSS 22 Statistics were used. In the Results Section for the task-switching data, we will focus on RTs, as there were no significant interaction with the factor Training Group for error rates. Mixing and switching costs were defined by two orthogonal contrasts. In the first contrast performance of single task trials were compared with non-switch and switch trials in mixed blocks (i.e., -2 1 1, mixing costs). In the second contrast performance within mixed blocks were compared between non-switch and switch trials (i.e., 0 - 1 1, switching costs). Thereby, mixing and switching costs are statistically independent of each other. As baseline differences in reaction times between younger and older adults can be substantial, when comparing performance costs between younger and older adults, we also analyzed the data on the basis of log-transformed reaction times that are less sensitive to group differences in baseline performance (e.g., Kray and Lindenberger, 2000; Karbach, 2008).

The advantage here is that mean differences between log-transformed RTs correspond to ratio scores (cf. Meiran, 1996) so that the interpretation of age differences, practice and transfer effects are based on relative changes instead of absolute changes. Unless reported otherwise, results were consistent with untransformed RTs. Testing for homogeneity of variance-covariance matrices was assessed by Box's M tests. In case of

violation of assumptions, Greenhouse-Geisser corrected *p*-values

For the evaluation of transfer effects, we also calculated Cohen's d or the standardized mean difference in performance between pretest and posttests (Verhaeghen et al., 1992). That is, the pretest-posttest differences (for each of the two groups) were divided by the pooled standard deviation for test occasions. We then corrected all d-values for small sample bias using the Hedges and Olkin correction factor (d') (Hedges and Olkin, 1985).

#### **RESULTS**

The results section consists of four parts. In the first part, we analyzed baseline differences between the training groups for all variables of interest. In the second part, we analyzed age and training group differences in the practice effects in the training phase. In the third and fourth part, we analyzed whether near and far transfer effects, respectively, varied across age and training groups.

#### **Group Differences in Baseline** Performance

At first we assessed whether there were baseline differences in the pretest measurement of the dependent variables of interest for near and far transfer measures between the five training groups (see Table 1). Therefore, pretest data were submitted to separate analyses of variance (ANOVA) for each indicator test with the between-subjects factors Age Group (younger adults/older adults) and Training Group (1/2/3/4/5). Neither the main effect for Training Group for the younger or the older adults (see **Table 1**, all p's > 0.13), nor the interaction with Age Group reached significance with dependent variables of interests, indicating no baseline differences.

#### Age and Training Group Differences in **Training Performance**

To demonstrate training gains we analyzed practice-induced reductions in switching costs across the two age groups and the four task-switching training groups. Given that we had no specific hypotheses regarding differences in training curves across the four training sessions we focused the analyses on comparisons between the performance in the first and fourth training session. Mean reaction times for all experimental variables that entered the ANOVA as well as switching costs and their reduction are shown in Table 2, separately for the four training groups and two age groups. In addition, the reduction of switching costs across the four sessions in the four training groups is displayed in Figure 2 separately for younger and older adults.

Training data were submitted to a four-way ANOVA including the within-subjects factors Session (1, 4) and Trial Type (switch, non-switch) and the between-subjects factors Age Group (younger adults, older adults) and Training Group (Group 2, Group 3, Group 4, Group 5). For the factor Training Group, we pre-specified three *a priori* contrasts according to our predictions. In the first contrast, we compared the performance between taskswitching groups that practiced with univalent stimuli versus

TABLE 2 | Mean reaction times (ms) and (SD) as a function of Session (1, 4), Trial type (non-switch, switch), and Training group (Group 3, Group 4, Group 5) separately for each Age group (younger adults, older adults) as well as switching costs, practice gains, and improvements of relative switching costs.

			Se	Session 1					Se	Session 4						
	Non-s	Non-switch	Swi	Switch	Switch	Switching costs	Non-switch	witch	Swi	Switch	Switch	Switching costs	Practi	Practice gains	Relative i	Relative improvement
Training group	N	(as)	N	(as)	W	(as)	N	(as)	N	(as)	N	(as)	W	(as)	M	(as)
Younger adults																
Group 2	592	(63)	721	(122)	129	(86)	501	(52)	540	(70)	38	(28)	91	(92)	14.1%	(0.10)
Group 3	724	(94)	950	(210)	225	(142)	592	(62)	652	(121)	88	(65)	138	(36)	15.1%	(0.9)
Group 4	595	(129)	757	(211)	163	(113)	514	(81)	574	(111)	09	(43)	103	(77)	15.2%	(0.10)
Group 5	703	(122)	626	(222)	236	(129)	564	(78)	299	(159)	102	(85)	134	(72)	15.8%	(0.10)
Older adults																
Group 2	848	(181)	1020	(244)	172	(87)	651	(63)	715	(111)	64	(43)	108	(62)	10.1%	(0.07)
Group 3	1110	(280)	1329	(373)	219	(181)	855	(509)	626	(267)	124	(124)	92	(102)	5.4%	(0.09)
Group 4	998	(198)	1119	(329)	253	(182)	889	(123)	798	(221)	110	(110)	143	(111)	13.8%	(0.13)
Group 5	1104	(223)	1440	(247)	337	(147)	847	(154)	1056	(243)	209	(111)	127	(143)	7.8%	(0.14)

Group 2 = Task-switching training with task cues and univalent stimuli; Group 3 = Task-switching training with task cues and bivalent stimuli; Group 4 = Task-switching training with task cues and univalent stimuli; Group 5 = Task-switching training without cues and bivalent stimuli

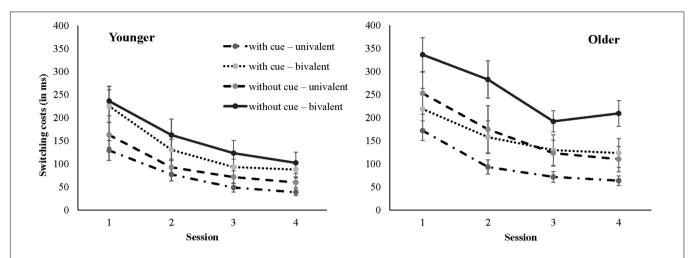


FIGURE 2 | Switching costs (in ms) as a function of session and task-switching training group separately for younger adults (Left) and older adults (Right).

bivalent stimuli (Training Group Contrast 1). In the second contrast, we compared the performance between groups that received *univalent* stimuli and practiced with task cues versus without task cues (Training Group Contrast 2). Finally, in the third contrast we compared the performance between groups that received *bivalent* stimuli and practiced with task cues versus without task cues (Training Group Contrast 3).

The results indicated a main effect of Age Group, F(1,128) = 92.94, p < 0.001,  $\eta^2 = 0.42$ , suggesting that older responded slower than younger adults. There were also main effects of Session, F(1,129) = 662.72, p < 0.001,  $\eta^2 = 0.84$ , and Trial Type, F(1,129) = 435.71, p < 0.001,  $\eta^2 = 0.77$ , as well as a reliable interaction between both, [Session × Trial Type: F(1,129) = 183.51, p < 0.001,  $\eta^2 = 0.59$ ], indicating the switching costs were reduced from the first to the fourth training session. Overall, this reduction was about 116 ms for younger adults and 118 ms for older adults (see **Table 2**), suggesting that younger as well as older adults showed large practice-related improvements in task switching (see also **Figure 2**).

Of most interest in the present study were effects of the training group conditions and their interactions with task switching and practice. Therefore, we only report significant effects of the corresponding interactions. As can be seen in Figure 2, the magnitude of switching costs varied across the task-switching training groups. Groups that practiced with bivalent stimuli showed larger switching costs than groups with univalent stimuli, [Trial Type × Training Group Contrast 1: F(1,122) = 8.28, p < 0.05,  $\eta^2 = 0.06$ ]. Comparing the two training groups that received bivalent stimuli the group that practiced without task cues showed larger switching costs than the group with task cues [Trial Type × Training Group Contrast 3: F(1,122) = 5.98, p < 0.05,  $\eta^2 = 0.05$ ]. Switching costs did not significantly differ between the two groups that received univalent stimuli (p = 0.57). All of these effects were not modulated by practice as the interactions between Session, Trial Type, and Training Group contrasts were non-significant (all p's > 0.11). Also, the four-way interactions between Session, Trial

Type, Training Group, and Age Group did not reach significance (all p's > 0.08).

In sum, as expected younger and older benefitted from practice in task switching in all four task-switching training groups and only the magnitude of switching costs varied across the training conditions. Switching costs were greatest with high demands on cognitive control induced by task uncertainty, that is, with the presence of ambiguous stimuli and the absence of task

#### **Near Transfer Gains and Its Maintenance**

First, we analyzed age differences in the overall near transfer gains, that is, the overall improvements in task switching for the five training groups. Mean reaction times for all experimental variables and training groups are shown separately for younger and older adults in **Tables 3**, **4**, respectively. Moreover, the reduction of mixing costs from pretest to posttest is displayed in **Figure 3A** for younger adults and in **Figure 3B** for older adults.

Data were submitted to a four-way ANOVA including the within-subjects factors Session (pretest, posttest) and Trial Type (single, non-switch, switch) and the between-subjects factors Age Group (younger adults, older adults) and Training Group (Group 1, Group 2, Group 3, Group 4, Group 5). For the factor Training Group we pre-specified four a priori contrasts according to our predictions. In the first contrast we compared the performance between the single-task group and the taskswitching groups (Training Group Contrast 1). In the second contrast we compared the performance between task-switching groups that received *univalent stimuli* and task-switching groups that received bivalent stimuli (Training Group Contrast 2). In the third contrast, we compared the performance between the group that received *univalent stimuli with* task cues and the group that received univalent stimuli without task cues (Training Group Contrast 3). In the fourth contrast, we compared the performance between the group that received bivalent stimuli with task cues and the group that received bivalent stimuli without task cues (Training Group Contrast 4).

TABLE 3 | Mean (M) reaction times and standard deviations (SD) for each trial type (single, non-switch, switch) as well as mixing and switching costs for younger adults separately for each training group at pretest, posttest, and follow-up.

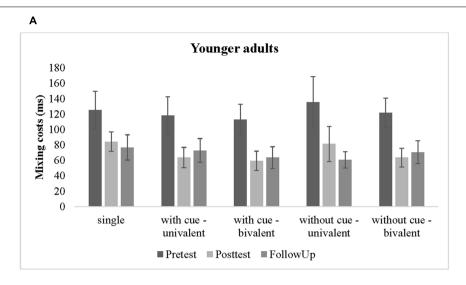
	Training group								
	Group 1 single – bivalent	Group 2 with cue – univalent	Group 3 with cue – bivalent	Group 4 without cue – univalent	Group 5 without cue – bivalent				
Trial type	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)				
Pretest									
Single	511 (49)	519 (47)	521 (71)	513 (78)	525 (58)				
Non-switch	597 (100)	599 (106)	590 (115)	602 (182)	599 (99)				
Switch	676 (139)	676 (150)	677 (135)	695 (231)	696 (134)				
Mixing costs	125 (96)	118 (98)	113 (80)	135 (137)	122 (76)				
Switching costs	79 (53)	77 (63)	87 (53)	93 (61)	97 (57)				
Posttest									
Single	469 (45)	472 (44)	474 (66)	481 (68)	480 (48)				
Ion-switch	523 (55)	509 (68)	501 (77)	526 (124)	514 (61)				
Switch	582 (87)	561 (107)	566 (101)	598 (181)	574 (98)				
Mixing costs	84 (50)	64 (53)	59 (50)	81 (94)	64 (49)				
Switching costs	59 (46)	52 (44)	65 (35)	72 (64)	60 (42)				
ollow-up									
Single	465 (29)	474 (44)	443 (33)	466 (51)	492 (40)				
lon-switch	516 (56)	525 (77)	486 (62)	499 (77)	528 (64)				
Switch	568 (96)	569 (105)	527 (72)	555 (102)	597 (114)				
Mixing costs	77 (63)	73 (58)	64 (46)	61 (43)	71 (57)				
Switching costs	53 (53)	45 (34)	41 (22)	56 (38)	69 (60)				

TABLE 4 | Mean (M) reaction times and standard deviations (SD) for each trial type (single, non-switch, switch) as well as mixing and switching costs for older adults separately for each training group at pretest, posttest, and follow up.

	Training group								
-	Group 1 single – bivalent	Group 2 with cue – univalent	Group 3 with cue – bivalent	Group 4 without cue – univalent	Group 5 without cue – bivalent				
Trial type	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)				
Pretest									
Single	680 (68)	721 (138)	659 (102)	701 (79)	689 (64)				
Non-switch	913 (155)	940 (231)	883 (179)	925 (176)	907 (141)				
Switch	1010 (199)	1047 (292)	978 (203)	1033 (204)	1007 (151)				
Mixing costs	282 (128)	272 (144)	271 (140)	278 (149)	268 (119)				
Switching costs	96 (106)	106 (108)	95 (59)	108 (65)	100 (84)				
Posttest									
Single	613 (70)	678 (108)	671 (110)	669 (84)	660 (79)				
Non-switch	787 (128)	829 (204)	744 (159)	832 (151)	782 (132)				
Switch	902 (157)	926 (236)	835 (202)	934 (194)	897 (146)				
Mixing costs	231 (101)	199 (137)	118 (117)	214 (98)	180 (83)				
Switching costs	115 (66)	97 (72)	91 (71)	102 (71)	115 (84)				
Follow-up									
Single	635 (88)	694 (150)	641 (80)	700 (117)	671 (80)				
Non-switch	821 (134)	874 (236)	784 (172)	891 (170)	789 (126)				
Switch	936 (165)	975 (275)	893 (228)	998 (182)	913 (154)				
Mixing costs	244 (97)	230 (163)	198 (142)	244 (104)	180 (93)				
Switching costs	115 (96)	101 (78)	109 (78)	107 (41)	123 (74)				

According to our predictions we focus on the interactions with training group. Here, we found that switching costs did not change differently from pretest to posttest across the training

groups (p = 0.84), but mixing costs changed differently from pretest to posttest across the training groups [Session  $\times$  Trial Type Contrast 1  $\times$  Training Group: F(4,158) = 3.55, p < 0.05,



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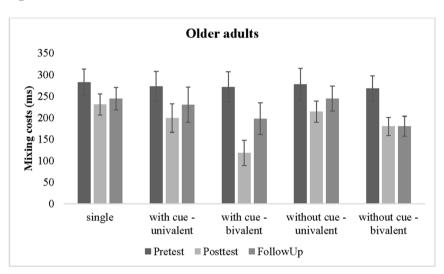


FIGURE 3 | Reduction of mixing costs from pretest to posttest to follow up (A) for younger adults and (B) for older adults.

 $\eta^2 = 0.08$ , and this effect was further modulated by age in tendency [Session × Trial Type Contrast 1 × Training Group × Age Group: F(4,158) = 2.20, p = 0.07,  $\eta^2 = 0.05$ ] (see also Figures 3A,B). The first training group contrast indicated a larger reduction of mixing costs from pretest to posttest for the task-switching training groups than for the single-task group [Session × Trial Type Contrast 1 × Training Group Contrast 1: F(1,154) = 6.33, p < 0.05,  $\eta^2 = 0.04$ , and this effect was no further modulated by age (p > 0.26). For the second training group contrast was also significant [Session × Trial Type Contrast 1 × Training Group Contrast 2: F(1,154) = 5.10, p < 0.05,  $\eta^2 = 0.03$ ] and this time the effect was further modulated by age [Session × Trial Type Contrast 1 × Training Group Contrast 1  $\times$  Age Group: F(1,154) = 4.02, p < 0.05,  $\eta^2 = 0.03$ ]. Therefore, we run separate ANOVAs for each age group. A larger reduction of mixing costs for the bivalent than

for the univalent training groups were only found in the older age group [Session × Trial Type Contrast 1 × Training Group Contrast 2: F(1,77) = 7.89, p < 0.05,  $\eta^2 = 0.09$ ] but not in the younger age group (p = 0.85). Finally, while the reduction of mixing costs did not differ between training groups that practiced with univalent stimuli with cues and without cues (p = 0.82), we found a difference in the reduction of mixing costs between the two bivalent groups at least in tendency [Session × Trial Type Contrast 1 × Training Group Contrast 4: F(1,154) = 3.17, p = 0.08,  $\eta^2 = 0.02$ ], that was again further modulated by age [Session × Trial Type Contrast 1 × Training Group Contrast 4 × Age Group: F(1,154) = 4.03, p < 0.05,  $\eta^2 = 0.03$ ]. Therefore, we again run separate ANOVAs for each age group. The larger reduction of mixing costs for the bivalent group with cues than without cues was only found in the older age group [Session  $\times$  Trial Type Contrast 1  $\times$  Training Group Contrast 4: F(1,77) = 6.19, p < 0.05,  $\eta^2 = 0.07$ ] but not in the younger age group (p = 0.86).

However, **Figure 3B** also shows that in the group of older adults mixing costs between the two task-switching training groups that practiced with univalent stimuli seemed to be not different from the single-task training group that practiced with bivalent stimuli. Therefore, we run a *post hoc* contrast and found that the difference between these training groups was indeed not significant (p = 0.66).

Second, to examine whether near transfer gains (i.e., the reduction of mixing costs) were maintained over a period of 6 months, relative to baseline performance, data were submitted to a four-way ANOVA including the within-subjects factors Session (pretest, follow-up) and Trial Type (single, non-switch, switch) and the between-subjects factors Age Group (younger adults, older adults) and Training Group (Group 1, Group 2, Group 3, Group 4, Group 5). For the factor Training Group the same four *a priori* contrasts were used as previously. The corresponding data are also plotted in **Figures 3A,B**.

The results indicated a larger reduction of mixing costs from pretest to follow up for the two task-switching training groups that practiced with bivalent than with univalent stimuli [Session × Trial Type Contrast 1 × Training Group Contrast 2: F(1,136) = 4.14, p < 0.05,  $\eta^2 = 0.03$ ]. However, the larger reduction of mixing costs in task-switching groups compared to the single-task training group disappeared (p = 0.21).

In sum, for younger adults we only found that the task-switching groups showed a larger reduction in mixing costs than the single task training group from pretest to posttest but these performance gains were not maintained over a longer period of time. In contrast, older adults showed larger gains for the two task-switching groups that practiced with bivalent than with univalent stimuli, hence for conditions with high inhibition demands, and these transfer gains, relative to initial task performance before training, were maintained over a time period of 6 months.

# Transfer Gains as a Function of Overlap to the Training Condition

To further examine whether transfer gains (i.e., the reduction in mixing costs) varied as a function of overlap between training conditions and transfer condition we also analyzed age differences in transfer gains separately for each of the four taskswitching training groups. The corresponding data are displayed in Figures 4A-D. They show that for most of the conditions transfer gains were larger for those conditions in which they were trained (highlighted by the black bars in Figures 4A-D) as compared to conditions in which the training shared only one feature either the cueing condition (with or without cues) or the interference condition (univalent or bivalent) (indicated by dark gray bars in **Figures 4A–D**) and smallest transfer gains are obtained for conditions that did not overlap with the two features of the training condition (see light gray bars in Figures 4A-D). To confirm this observation, mixing costs were submitted to an ANOVA including within-subjects factors Session (pretest, posttest) and Switching Condition (with cues/univalent, with

cues bivalent, no cues/univalent, no cues/bivalent) and the between-subjects factor Age Group (younger, older) separately for each of the four task-switching training groups. We specified contrasts along to our expectation that training gains are largest for the condition that overlapped in demands on working memory and inhibition between training and transfer situation as compared to the other conditions and then we tested whether there were significant differences in gains to those conditions that overlapped either in demands on WM or inhibition between training and transfer situation.

#### Task-Switching Training Group (with Cues/Univalent)

As can be seen in **Figure 4A**, only for the older adults we found a larger reduction in mixing costs for the condition that overlapped with the training condition as compared to all other conditions  $[F(1,81)=6.01,\ p<0.05,\ \eta^2=0.07]$ . We also obtained a larger reduction in mixing costs for the trained condition (with cues/univalent) as compared to the condition that only shared the univalent feature but not the cueing condition for both younger and older adults  $[F(1,162)=18.50,\ p<0.01,\ \eta^2=0.10]$ . Finally, we found age differences in the reduction of mixing costs between the trained condition and the condition that shared the cueing situation (with cues) but with bivalent stimuli  $[F(1,161)=4.28,\ p<0.05,\ \eta^2=0.03]$ .

#### Task-Switching Training Group (with Cues/Bivalent)

For this training group we found larger reductions in mixing costs for the condition (with cues/bivalent) that corresponded to the training condition as compared to all other three conditions  $[F(1,162)=8.95,\ p<0.01,\ \eta^2=0.05]$  and this effect was more pronounced in the older than in the younger adults  $[F(1,161)=4.26,\ p<0.05,\ \eta^2=0.03]$ . We also obtained a larger reduction in mixing costs for the condition corresponding the training condition than the condition sharing only the cueing condition (with cues) but with univalent stimuli  $[F(1,162)=8.53,\ p<0.01,\ \eta^2=0.05]$  and again this effect was more pronounced in older than in younger adults  $[F(1,161)=4.28,\ p<0.05,\ \eta^2=0.03]$ . Interestingly, the reduction in mixing costs did not differ for conditions that shared bivalent stimuli (p=0.86) and age differences in this comparison were absent (p=0.27).

## Task-Switching Training Group (without Cues/Univalent)

Similar to the previous training group we found a larger reduction in mixing costs for the condition (without cues/univalent) that corresponded to the training condition as compared to all other conditions [ $F(1,162)=3.99, p<0.05, \eta^2=0.03$ ]. Results also revealed a larger reduction in mixing costs for the condition corresponding the training condition than for the condition sharing univalent stimuli [ $F(1,162)=8.53, p<0.01, \eta^2=0.05$ ] but not for conditions sharing the cueing condition (p=0.50). There were no significant age differences in these effects (all p's >0.11).

### Task-Switching Training Group (without Cues/Bivalent)

Again, similar to the two previous training groups we found a larger reduction in mixing costs for the condition (without

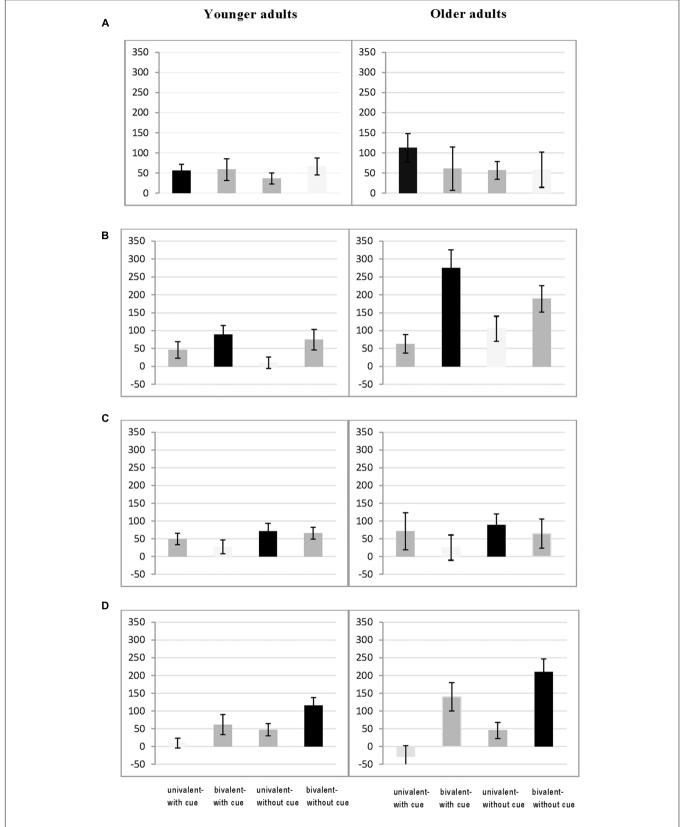


FIGURE 4 | Reduction of mixing costs from pretest to posttest separately for younger adults (left) and for older adults (right) as a function of overlap between the training and transfer condition for the Task-switching Group 1 (A) Group 2 (B) Group 3 (C) and Group 4 (D).

cues/bivalent) that corresponded to the training condition as compared to all other three conditions  $[F(1,162) = 11.89, p < 0.01, \eta^2 = 0.07]$ . Results also revealed a larger reduction in mixing costs for the condition corresponding the training condition than for the condition sharing the cueing condition  $[F(1,162) = 18.50, p < 0.01, \eta^2 = 0.10]$  but not for conditions sharing the interference condition (p = 0.87). Again there were no significant age differences in all of these effects (all p's > 0.26).

In sum, with the exception of the first training group the results indicated that a higher overlap between the training and the transfer condition lead to larger reductions in mixing costs than compared to the other conditions. For conditions that overlap in high inhibition demands (bivalent stimuli) or in high WM demands (without cues) we did not find a difference in the amount of transfer, neither for younger nor for the older adults. Age differences were only found in the first two training groups in a way that older showed more specific transfer effects as compared to younger adults.

#### **Far Transfer Effects**

To assess far transfer of the task-switching training to WM span and updating, inhibition and fluid intelligence measures, we first proved the correlations between the three measurement times of the parallel test versions. Correlations ranged between r=0.69 and r=0.70 for the Digit Backward, and between r=0.40 and r=0.59 for the Reading and Counting Span, between r=0.42 and r=0.74 for the 2-back, between r=0.23 and r=0.27 for the 3-back task, between r=0.10 and r=0.30 for the Color-Stroop interference score, between r=0.26 and r=0.23 for the Number–Stroop interference score, between r=0.11 and r=0.12 for the AX–CPT interference costs score, and between r=0.83 and r=0.86 for the Raven score. Hence, especially the interference costs and n-back measures were not very reliable across measurement times and therefore the results should be taken with caution.

The corresponding dependent variables were submitted to three-way ANOVAs, including the within-subjects factors Session (pretest, posttest) and the between-subjects factors Age Group (younger adults, older adults) and Training Group (Group 1, Group 2, Group 3, Group 4, Group 5). The corresponding data are shown in **Table 5** for the younger adults and in **Table 6** for the older adults. As can be seen in both tables, most of the variables did not change substantially from pretest to posttest. In the following, we will only report interactions of interest, such as two-way interactions between session and training group or three-way interactions between session, training group, and age group.

#### Working-Memory Span

For neither of the three WM variables we found significant two-way or three-way interactions (all p's > 0.09). To increase the reliability of measurement we also used a composite score of all three measures by computing the mean of the three z-transformed measures. The correlations between pretest and posttest measurement of this composite measure was r = 0.74 for younger adults and r = 0.76 for older adults. Results of the ANOVA indicated that the group contrast comparing

single-task and task-switching groups showed a tendency for an interaction with Session, F(1,154) = 2.95, p = 0.09,  $\eta^2 = 0.02$ . We also determined the effect sizes for both age groups separately that were low and negative for the single task training groups (d' = -0.02 for younger adults and d' = -0.35 for older adults) but also small for the task-switching groups (d' = 0.12 for younger adults and d' = -0.01 for older adults). Hence, we found no evidence for improvements in WM capacity after task-switching training.

#### **Working-Memory Updating**

Again for neither of the WM updating measures we obtained significant two or three-way interactions (all p's > 0.19). Again to increase the reliability of measurement we computed composite scores, that is, means of the z-transformed scores of the 2-back and 3-back task (only for younger adults). The group contrast comparing single-task and task-switching groups showed no significant difference in performance between pre- and post-test (p = 0.35).

#### Inhibition

For the three inhibition measures we found no significant two-way and three-way interactions for the Color–Stroop interference effect (all p's > 0.12) and the AX–CPT interference score (all p's > 0.19). Only for the Number–Stroop interference effect we found an interaction between session and the group contrast comparing the single task training group with all task-switching training groups, F(1,158) = 3.89, p = 0.05,  $\eta^2 = 0.02$ , indicating a larger decease in interference costs from pretest to posttest for the task-switching than the single task groups. As correlations between the three interference costs measures were rather low ranging between r = 0.04 and r = 0.20 we did not compute a composite measure for these measures.

#### Fluid Intelligence

For the performance on the Raven's we also found no interactions between session and training group contrasts or between session, age group, and training group contrasts (all p's > 0.13). There was only a tendency for an interaction between session and the training contrast comparing the single with all task-switching groups, F(1,153) = 3.40, P = 0.07,  $\eta^2 = 0.02$ . However, as can be seen in **Tables 5**, **6**, these changes were in opposite to expectations as Raven's performance declined and in tendency more for the treatment groups than for the active control group. Effects sizes for the single task training groups were rather small and positive for the younger adults (d' = 0.08) and for the older adults (d' = 0.17) and negative for the task-switching training groups for the younger adults (d' = -0.38) as well as for the older adults (d' = -0.09).

#### DISCUSSION

The main goal of the present study was to systematically investigate the impact of WM and inhibition demands on improvements in task switching, its maintenance and near and far transfer effects as well as age differences therein. In particular, we aimed at identifying whether and what kind of control

TABLE 5 | Means (M) and standard deviations (SD) for the far transfer measures as a function of session (pretest/posttest) separately for the five training groups for the younger age group.

			Training group			
	Group 1 single task – bivalent stimuli	Group 2 with cue – univalent stimuli	Group 3 with cue – bivalent stimuli	Group 4 without cue – univalent stimuli	Group 5 without cue – bivalent stimuli <i>M (SD)</i>	
Session	M (SD)	M (SD)	M (SD)	M (SD)		
Counting s	pan (% correct items)					
Pretest	82 (9)	82 (14)	81 (13)	82 (11)	78 (12)	
Posttest	83 (12)	86 (14)	80 (14)	81 (11)	80 (12)	
Reading sp	oan (% correct items)					
Pretest	81 (10)	76 (14)	78 (13)	76 (18)	76 (15)	
Posttest	77 (12)	78 (15)	78 (16)	79 (15)	82 (10)	
Digit backy	ward (% correct items)					
Pretest 36 (9)		36 (7)	36 (11)	35 (11)	36 (8)	
Posttest	41 (9)	37 (8)	40 (9)	37 (12)	42 (16)	
2-back (pro	portion of hits minus false a	ılarms)				
Pretest	0.50 (0.26)	0.45 (0.30)	0.41 (0.26)	0.41 (0.32)	0.58 (0.19)	
Posttest	0.58 (0.20)	0.52 (0.19)	0.50 (0.25)	0.45 (0.28)	0.60 (0.20)	
Color-Stro	op Interference (ms)					
Pretest	38.2 (45.9)	27.4 (57.3)	13.1 (50.7)	37.3 (31.7)	27.1 (52.2)	
Posttest	27.3 (26.0)	19.4 (52.9)	36.1 (49.3)	22.7 (40.0)	15.6 (34.4)	
Number-St	troop Interference (ms)					
Pretest	13.2 (30.6)	20.8 (44.1)	36.2 (28.8)	10.9 (37.4)	26.9 (32.9)	
Posttest	15.4 (21.2)	7.9 (34.0)	12.7 (36.3)	24.2 (36.2)	12.6 (26.4)	
AX-CPT In	terference (ms)					
Pretest	75 (63)	80 (76)	141 (101)	120 (73)	125 (108)	
Posttest	86 (51)	77 (69)	91 (53)	102 (65)	118 (65)	
Raven						
Pretest	10.9 (2.4)	11.4 (3.2)	11.4 (2.2)	11.5 (2.4)	11.6 (2.7)	
Posttest	11.0 (1.6)	9.8 (3.2)	11.5 (1.8)	10.0 (2.8)	10.5 (2.6)	

processes may contribute to the transfer of switching training to new switching situations and other cognitive control tasks that varied in WM and inhibition demands. To achieve these goals we created five different training conditions that varied in switching (single task versus mixing tasks), inhibition (bivalent versus univalent stimuli) and WM demands (without versus with task cues). We compared younger and older adults in transfer and maintenance effects across the different switching training conditions with a pretest-training-posttest follow-up design.

Results of this training study revealed several important new insights about which cognitive processes are critical for the transfer and maintenance of training effects in cognitive control in younger and older adults. At first, the analysis of practice data showed that our experimental manipulations were successful and lead to variations in the magnitude of switching costs. Switching costs were largest in the groups that received bivalent stimuli and no task cues (high WM demands) as compared to the groups that received task cues (low WM demands), and switching costs were larger for groups practicing with bivalent (high inhibition demands) than with univalent stimuli (low inhibition demands). Also note that for the groups receiving univalent stimuli switching costs were not different depending on whether task cues were present or not. As for univalent stimuli task cues

are in principle redundant subjects may adopted a strategy to wait for the target presentation in order to select the appropriate response without advance preparation. More importantly for the interpretation of transfer effects is that all training and age groups showed a substantial reduction of switching costs throughout the four practice sessions. Effect sizes for the practice gains varied between d'=1.21 and d'=1.42 for the younger adults and between d'=0.62 and d'=1.59 for the older adults.

A second noteworthy finding is that we obtained age-differential effects in the transfer of training gains to new untrained switching situations as a function of training demands. Overall, younger adults showed a larger reduction in mixing costs from pre- to post-test after task-switching training as compared to the active control group independently of the WM and inhibition demands throughout the training. This seems to suggest that training in switching being most critical in that age group but the observed training benefit was not stable over time. One may argue that the variations in WM and inhibition demands were not different and challenging enough in this age group to induce a mismatch between training demands and actual level of cognitive functioning but the results from the practice phase clearly indicated a substantial variation in the magnitude of switching costs also in the younger age group a

TABLE 6 | Means (M) and standard deviations (SD) for the far transfer measures as a function of session (pretest/posttest) separately for the five training groups for the older age group.

			Training group			
	Group 1 single task – bivalent stimuli	Group 2 with cue – univalent stimuli	Group 3 with cue – bivalent stimuli	Group 4 without cue – univalent stimuli	Group 5 without cue – bivalent stimuli  M (SD)	
Session	M (SD)	M (SD)	M (SD)	M (SD)		
Counting s	pan (% correct items)					
Pretest	76 (15)	72 (12)	77 (17)	74 (13)	69 (11)	
Posttest	73 (15)	76 (19)	77 (11)	81 (11)	74 (16)	
Reading sp	oan (% correct items)					
Pretest	74 (14)	73 (15)	73 (14)	77 (12)	72 (16)	
Posttest	66 (16)	71 (14)	71 (17)	71 (14)	70 (19)	
Digit back	ward (% correct items)					
Pretest	30 (7)	25 (12)	26 (8)	22 (9)	29 (12)	
Posttest	31 (10)	28 (11)	28 (8)	25 (9)	29 (10)	
2-back (pro	pportion hits minus false alar	rms)				
Pretest	Pretest 0.41 (0.27) 0.		0.40 (0.28)	0.46 (0.26)	0.46 (0.31)	
Posttest	0.49 (0.25)	0.52 (0.21)	0.49 (0.22)	0.40 (0.30)	0.56 (0.15)	
Color-Stro	op Interference (ms)					
Pretest	121 (67)	85 (67)	72 (40)	112 (141)	111 (93)	
Posttest	osttest 105 (104) 107 (75)		61 (42)	86 (90)	131 (77)	
Number-St	troop Interference (ms)					
Pretest	6.15 (64)	33.4 (56)	3.70 (43)	31 (46)	48.4 (64)	
Posttest	33.5 (92)	31.6 (66)	33.1 (60)	4.87 (56)	14.1 (52)	
AX-CPT In	terference (ms)					
Pretest	Pretest 123 (117) 132 (123)		114 (100)	129 (177)	96 (251)	
Posttest	99 (147)	123 (115)	108 (111)	154 (129)	146 (101)	
Raven						
Pretest	5.28 (2.3)	5.27 (2.2)	5.33 (2.3)	4.69 (2.7)	4.88 (2.6)	
Posttest	5.33 (2.2)	5.00 (2.1)	4.67 (1.8)	4.38 (1.2)	5.00 (2.2)	

finding that speaks against this potential explanation. Hence, training in task switching seems to be rather narrow in scope in the group of younger adults, in line with other findings (e.g., Pereg et al., 2013). In contrast, the older adults showed larger performance improvements in task switching when they practiced task switching with bivalent stimuli instead of univalent stimuli, suggesting that inhibition demands are critical in that age group. Notably, not only inhibition counts for the elderly given that the single task training group has also received bivalent stimuli but this condition did not require to maintain both tasks and to switch between them. Indeed our analysis revealed that the active control group did not differ from the other two task-switching groups practicing with univalent stimuli. These findings suggest that control processes required for resolving task interference in dual-task like switching situations are most critical for inducing transfer effects, and moreover, we were able to show for the first time that elderly adults were able to maintain these benefits at least for 6 months. In general, our results are consistent with previous task-switching studies by showing switching improvements in a new, untrained switching situation in younger adults (Pereg et al., 2013; von Bastian and Oberauer, 2013) as well as in older adults (Bherer et al., 2005; Karbach and Kray, 2009; Anguera et al., 2013). They are also consistent with

the claim by Anguera et al. (2013) that the training in resolving interference between two competing tasks (as required in dualtask and switching situations) is a key component for inducing transfer of training in older adults. The present study directly tested this idea by systematically manipulating the amount of interference between tasks while switching between them and in support of this view transfer of training was restricted to the bivalent training conditions in the elderly.

A third new finding of the present study is that the transfer of switching training depends on the amount of overlap between training and transfer situation and by this on the type of cognitive control processes practice during the training sessions. Comparing the reductions of mixing costs within the four taskswitching training groups indicated - with the exception for the young group with lowest demands on cognitive control (with cues/univalent stimuli) – a general pattern of larger transfer gains with more overlap between the training and the transfer situation in younger as well as in older adults. However, reductions in mixing costs did not differ when training and transfer situation required high WM demands (without cues) or high inhibition demands (bivalent stimuli), again suggesting that transfer of training in task switching only occurs when the training situation is challenging, that is, when WM updating and interference

control is required and practiced. Our findings are consistent with findings from study by von Bastian and Oberauer (2013) who found near transfer from a cued-task switching training to an uncued switching task with bivalent stimuli. In contrast, one study by Pereg et al. (2013) did not find evidence for a transfer to similar switching situations, but in this study only WM demands were varied by increasing the length of task-repetition trials (without cues) and presenting cues in a random manner. Therefore, these findings are not directly comparable to those of the present study. However, the overall findings clearly show that the amount of transfer of a switching training is strongly dependent on the overlap between training and transfer situation and which type of control processes are trained, and by this, transfer of switching training is more narrow in scope as previously assumed (cf. Karbach and Kray, 2009).

Finally, in contrast to our previous findings results of the present study did not replicate the broad transfer to other cognitive tasks, more in line with other recent task-switching studies (Zinke et al., 2012; Pereg et al., 2013; von Bastian and Oberauer, 2013). Several reasons might explain this discrepancy in findings across both studies. First, we created and applied parallel versions of each test and task. We did this in the present study in order to reduce repeated measurement effects as we had three measurement times in our training design. Although correlations between the three measurement times were moderate to high for the WM span measures and the fluid intelligence test, especially the interference costs scores were not reliable across time and also did not correlate with each other, which in turn strongly decreases the likelihood to obtain far transfer effects. Second, we changed the stimulus material in the training and transfer switching tasks as we manipulated the amount of interference (bivalent and univalent stimuli) in the present study. In contrast, in the Karbach and Kray (2009) study we used pictures that integrated features of both tasks within the same object, such as a red apple and a black- and white printed tomato, which makes it difficult to selectively attend to only one currently relevant task feature and by this increase cognitive control demands. In the present study, we have used digit-letter combinations in which features of both tasks appeared side-by-side and therefore may are easier to selectively attend to. Interestingly the only measure in which we observed far transfer effects was the Number Stroop task that overlaps with the training task in the type of stimuli (i.e., digits), pointing to stimulus-specific effects in the transfer of training in task switching in the present study. Third, during training the type of switching tasks remained the same and the demands on cognitive control were much lower in comparison to the previous study (here all training groups received bivalent stimuli), which may limited the likelihood to induce transfer effects to other cognitive tasks as well as the power to detect them. In order to reduce such stimulusspecific as well as task-specific effects further studies need to include various stimulus domains and different task sets in their training intervention in order to foster the transfer of training.

Finally, some limitations in the interpretation of our findings should be noted. First, we only reported relative improvements

from the first to the forth practice session, ignoring potential age and/or group differences in learning curves. However, most important here was to show that we found the expected effects of our experimental manipulation namely differences in switching costs as a function of demands on inhibition and working memory and that we obtained improvements on switching for all groups. Second, given the complexity of our training design even a sample size of 16 participants in each group may was insufficient to detect smaller effects of experimental manipulations especially for the follow-up results that were based on an even smaller n for each group. Third, one may argue that a training intervention with only four practice sessions was rather short (as compared to some other training studies) and that such short interventions are unlikely to induce prolonged cognitive plasticity. We did not apply a longer practice phase to better compare our results to previous findings. Notably in this respect is, however, that it has also been shown that very intense training interventions sometimes lead to a lack of motivation and results in less transfer (cf. Toril et al., 2014). Finally, although we argue for low reliabilities of the far transfer measures across the three measurement times as a potential source for the lack of far transfer effects in the present study it is also conceivable that low reliability is caused by inter-individual variability of training effects in these measures. However, as we have no information about the parallel test reliabilities of these measures at pretest from an independent sample we cannot finally conclude on the reasons for a failure in far transfer. Hence, this point has to be carefully considered in future training research.

To summarize and conclude, differential cognitive control components are critical for inducing transfer of training in task switching in younger and older adults. While for younger adults practice in switching leads to larger transfer gains independently of inhibition and WM demands, older adults strongly profit from practice in resolving interference between two competing tasks. Our findings also indicate that transfer gains vary with the degree of overlap between training and transfer tasks and by this with the type of control processes involved. Hence transfer of training is possible when the training is challenging but it is also specific to the trained processes.

#### **AUTHOR CONTRIBUTIONS**

Both authors were involved in planning the study design. Analysis of data and their presentation was conducted by FB and JK wrote the most parts of the paper.

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# Development and Plasticity of Cognitive Flexibility in Early and Middle Childhood

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Cognitive flexibility, the ability to flexibly switch between tasks, is a core dimension of executive functions (EFs) allowing to control actions and to adapt flexibly to changing environments. It supports the management of multiple tasks, the development of novel, adaptive behavior and is associated with various life outcomes. Cognitive flexibility develops rapidly in preschool and continuously increases well into adolescence, mirroring the growth of neural networks involving the prefrontal cortex. Over the past decade, there has been increasing interest in interventions designed to improve cognitive flexibility in children in order to support the many developmental outcomes associated with cognitive flexibility. This article provides a brief review of the development and plasticity of cognitive flexibility across early and middle childhood (i.e., from preschool to elementary school age). Focusing on interventions designed to improve cognitive flexibility in typically developing children, we report evidence for significant training and transfer effects while acknowledging that current findings on transfer are heterogeneous. Finally, we introduce metacognitive training as a promising new approach to promote cognitive flexibility and to support transfer of training.

Keywords: cognitive flexibility, intervention, childhood, executive functions, metacognition, DCCS, task switching

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#### INTRODUCTION

Cognitive flexibility, the ability to shift between different tasks or goals, is considered a key aspect of executive functions (EF) allowing individuals to regulate their thoughts and actions adaptively (e.g., Miyake et al., 2000; Jurado and Rosselli, 2007). In the literature, it is also referred to by shifting, attention switching, or task switching, and includes both the ability to disengage from irrelevant information in a previous task and to focus on relevant information in a forthcoming task (Monsell, 2003). Thus, cognitive flexibility enables to think divergently, change perspective and adapt to a continuously changing environment.

When it comes to the structure of EF, earlier models have either assumed that it is a unitary construct (e.g., Duncan et al., 1997) or a set of dissociable control components (e.g., Stuss and Alexander, 2000). More recent approaches have shown the unity and diversity of EF in integrative frameworks (e.g., Miyake et al., 2000; Garon et al., 2008). The Miyake model, for instance, assumes that the core EF skills entail working memory (WM), inhibitory control, and cognitive flexibility. Importantly, this structure is subject to developmental changes, with a shift from a single latent EF

factor to separate component processes from early childhood to school age and adolescence (e.g., Huizinga et al., 2006; Wiebe et al., 2008, 2011).

Importantly, EF in general and cognitive flexibility in particular contributes to a number of important life outcomes, such as academic achievement (review: Titz and Karbach, 2014). Colé et al. (2014), for instance, showed that cognitive flexibility predicted reading skills in second graders and a recent meta-analysis showed that cognitive flexibility was a significant predictor for both math and reading skills in children between the ages of 4 and 13 years (Yeniad et al., 2013). Given the strong relationship between flexibility and achievement, it is not surprising that many studies have aimed at training flexibility in order to improve children's performance in the classroom (review: Titz and Karbach, 2014; meta-analysis: Schwaighofer et al., 2015). We will focus on such training effects in the last section of this review. In the upcoming section, we will first describe the development of cognitive flexibility.

#### **DEVELOPMENT OF COGNITIVE FLEXIBILITY**

Infants within their first year of life already exhibit fundamental forms of EF (Carpenter et al., 1998), but the core components (WM, inhibition and flexibility; Miyake et al., 2000) rapidly develop during the preschool years (Hughes, 1998). Research focusing on the development across the lifespan demonstrates that EF continues developing throughout childhood (e.g., Davidson et al., 2006) well into adolescence (e.g., Huizinga and van der Molen, 2007) and early adulthood (e.g., Anderson et al., 2001). In this review, however, our focus will be on the preschool and elementary-school age. We will illustrate developmental changes in flexibility by referring to two widely used paradigms assessing children's cognitive flexibility, the Dimensional Change Card Sort task (DCCS; Zelazo, 2006) and the task-switching paradigm (Monsell, 2003).

Most studies investigating preschoolers applied the DCCS to test cognitive flexibility. In this task, children are shown cards with pictures displaying two dimensions (e.g., color and shape) and are told to sort these cards by one dimension (e.g., by color) (pre-switch phase). At some point, participants are told to sort the cards by the other dimension (i.e., by shape) (post-switch phase). While children from the age of 4 years are able to switch the rules, 3-years-old typically perseverate and keep applying the first rule when they should apply the second one (e.g., Zelazo, 2006; Doebel and Zelazo, 2015). Performance continues to improve with age, as children are able to apply higher-order rules and handle more complex tasks (e.g., Chevalier and Blaye, 2009; Diamond, 2013), such as the task-switching paradigm. In this task, children are instructed to perform two tasks (A and B), e.g., two simple categorization tasks. In single-task blocks, participants perform both tasks separately (e.g., AAA, BBB), but in mixed-task blocks, they have to switch between both tasks (e.g., AABBAABB). This paradigm allows assessing two different components of cognitive flexibility - the ability to switch from one rule/task to another as well as the maintenance and selection of task sets in WM.

Karbach and Kray (2007) tested 5- to 6-years-old and 9-years-old on a cued task-switching paradigm. In task A, children had to categorize stimuli as either fruits or animals and in task B they had to indicate if the picture was presented in color or gray. Results showed an age-related improvement in the ability to maintain and select tasks, but not in the ability to switch between tasks. These different developmental trajectories of the processes subserving cognitive flexibility were confirmed by other studies applying switching tasks and investigating a wider range of ages (e.g., Cepeda et al., 2001; Crone et al., 2004; Reimers and Maylor, 2005; Huizinga and van der Molen, 2007; Kray et al., 2008). For instance, Huizinga and van der Molen (2007) examined the developmental change in switching and maintenance and found that children reached adult levels of switching abilities by the age of 11 years, while task maintenance abilities only matured at the age of 15 years. In sum, these findings point to an earlier maturation of task-switching than task-maintenance and selection abilities.

Developmental trajectories of EF are have been linked to maturational changes of the prefrontal cortex (PFC) and associated cortical and subcortical structures, including parietal regions and basal ganglia (e.g., Casey et al., 2005; Bunge and Wright, 2007). Some regions within the PFC, such as the orbitofrontal cortex, reach structural maturity at an earlier age, whereas others, such as the dorsolateral PFC, show a more protracted maturational time course (Gogtay et al., 2004). There is evidence - including studies using the DCCS and the task-switching paradigm - suggesting that those differences in structural maturation are paralleled by changes in functional maturation and hence may account for distinct developmental trajectories among EFs (Bunge and Zelazo, 2006).

For instance, a study by Moriguchi and Hiraki (2009) assessed 3- and 5-year-old children as well as adults with the DCCS task using NIRS (near-infrared spectroscopy). Results for the 3-years-old indicated that only some 3-years-old who passed the task showed significant activation in the right inferior PFC. In contrast, 5-years-old and adults showed this activation bilaterally (see also Moriguchi and Hiraki, 2014). This finding was consistent with another longitudinal study (Moriguchi and Hiraki, 2011) testing children at the age of 3 and 4 years. In contrast to age 3, children at age 4 passed the task and showed an increasing activation in the left inferior PFC (cf. Morton et al., 2009). Together with the finding that functional connectivity between the lateral PFC and inferior parietal cortex increases as children age (Ezekiel et al., 2013), these findings add to the evidence indicating that the PFC is a key player in the development of cognitive flexibility.

Studies using a task-switching paradigm confirm these age differences in brain activation. Rubia et al. (2006), for instance, found age-related increases in the recruitment of several brain regions that have been implicated in cognitive flexibility, including right inferior PFC, left parietal cortex, anterior cingulate cortex (ACC), and striatum. Moreover, there is neuroscientific evidence supporting the different developmental trajectories of task switching and task maintenance/selection: Crone et al. (2006) tested children, adolescents and adults and found an adult-like pattern of activation for task switching in the pre-supplementary motor area by adolescence. In contrast, the activation for task maintenance and selection in the ventrolateral PFC differed among children, adolescents, and adults (see Wendelken et al., 2012, for similar patterns of activation in children and adults, but different timing, pointing more to a change in the temporal dynamics rather than qualitative changes during development).

Taken together, the behavioral and neuroimaging results demonstrate that cognitive flexibility rapidly increases during early and middle childhood, suggesting that this may be a period of high plasticity and malleability sensitive to developmental as well as environmentally driven changes. It is not surprising then that much research focused on interventions designed to support the development of EF. These interventions range from school and curriculum-based programs to physical and cognitive training regimes (for reviews see Diamond, 2012; Karbach and Unger, 2014).

#### PLASTICITY OF COGNITIVE FLEXIBILITY – TRAINING AND TRANSFER EFFECTS

When it comes to training of EF, most of the existing developmental studies have certainly targeted WM (for reviews see Könen et al., 2016; Rueda et al., 2016). However, there are a handful of studies training cognitive flexibility in early and middle childhood. While some have trained multiple components of EF at the same time (e.g., Röthlisberger et al., 2012; Traverso et al., 2015), others have focused specifically on cognitive flexibility. We will illustrate this line of research by reviewing interventions applying the DCCS and the task-switching paradigm. We will report training effects and also evidence for transfer of training-related gains to untrained tasks and abilities, which recently has been discussed very controversially in the community (e.g., Shipstead et al., 2012).

Kloo and Perner (2003) trained 3- and 4-year-old children on the DCCS. Before and after training, the children performed the DCCS and a false-belief task (as well as a number of control tasks) including a novel version of the DCCS with different test and target cards at post-test. Children in the DCCS training group showed larger improvements on the DCCS and the false-belief task than children in the control group. They also outperformed the control group on the novel DCCS task. Thus, training did not only benefit cognitive flexibility but also transferred to false-belief understanding. Also training DCCS performance, van Bers et al. (2014) studied the effects of feedback on cognitive flexibility in 3-years-old. Providing feedback on the post-switch sorting improved DCCS performance compared to a standard condition without feedback. Importantly, these gains transferred to a novel version of the DCCS administered immediately after training as well as 1 week later.

In school-aged children, a number of studies have applied the task-switching paradigm to train cognitive flexibility. Adopting a lifespan approach, Cepeda et al. (2001) tested a sample ranging from 7–82 years of age on single-task and mixed-task blocks (N=152). After three sessions of training, participants – and

particularly children – significantly improved task maintenance and selection (Kray et al., 2008).

Following up on these training gains, other studies investigated whether task-switching training also transfers to untrained tasks and domains (e.g., Karbach and Kray, 2009; Zinke et al., 2012). Karbach and Kray (2009) had children (8–10 years of age) as well as younger and older adults (N = 168) perform four sessions of task-switching training. Results showed that training improved performance in an untrained switching task compared to a control group performing single-task training. Further, training also improved inhibition, verbal and visuo-spatial WM and fluid intelligence. Based on the transfer to WM and inhibition, another study tested the effects of task-switching training in children with ADHD because they usually show significant deficits in these domains. And indeed, four sessions of switching training resulted in significant improvements in an untrained switching task, inhibition and WM in 7- to 12-year-old boys with ADHD (N = 20; Kray et al.,

These findings indicate that training cognitive flexibility may be a key factor for improving other dimensions of EF. Still, it has to be noted that transfer was less pronounced in other studies: Zinke et al. (2012) assessed the effects of task-switching training in10- to 14-years-old (N=80). After three sessions of training, participants showed significant training gains and also transfer to an untrained switching task, but no transfer to inhibition. These effects mirror data from 8- to 11-years-old performing task-switching training embedded in a game environment (Dörrenbächer et al., 2014).

Thus, training regimes based on the DCCS and task-switching yielded significant improvements in cognitive flexibility across childhood and adolescence. Moreover, there is evidence showing that they can result in transfer to other EF dimensions, even though results on transfer of switching training are heterogeneous, just as they are for other types of cognitive training (for reviews, see Karbach and Kray, 2016; Könen et al., 2016). However, the existing studies almost exclusively analyzed data on the group level and ignored individual differences in training-induced gains. Given that even individuals participating in exactly the same training regime usually highly differ in their training outcomes (for reviews see Könen and Karbach, 2015; Katz et al., 2016), it is crucial to study individual differences in baseline performance as well as the individual performance development during training to understand these differential outcomes. Previous studies, for instance, showed that EF training often resulted in compensation effects, indicating that participants with lower baseline performances benefitted more (e.g., Cepeda et al., 2001; Bherer et al., 2008; Karbach and Kray, 2009; Zinke et al., 2012) and that individual differences in age and fluid intelligence (Bürki et al., 2014), motivational aspects (Katz et al., 2016), and the amount of training gain (e.g., Jaeggi et al., 2011) contributed to the success of training interventions. However, the underlying mechanisms are still largely unknown, especially in early childhood.

Another aspect that gains more and more attention in the field of training research is the question which aspects of intervention designs moderate training-induced gains. While current meta-analyses have tested effects related to the intensity, frequency and adaptivity of training, just to name a few (e.g., Karbach and Verhaeghen, 2014; Au et al., 2015; Schwaighofer et al., 2015), other features - such as the instructional design of training - have received less attention. However, since EF entails higher-level cognitive processes, it has been proposed that metacognitive processes, i.e., reflecting on one's own thinking and actions, may be important for the development and plasticity of EF (e.g., Zelazo et al., 2003; Chevalier and Blaye, 2016). This aspect has been investigated in a few recent studies. Espinet et al. (2013) showed across three experiments that training with corrective feedback and instruction to reflect on the task led to substantial improvements in DCCS performance in 2- to 4-years-old. Compared to controls, trained children benefitted more on an untrained version of the DCCS. Moreover, they showed a significant reduction of the N2 amplitude (an indicator of conflict detection) during DCCS performance and at the same time an increase in reaction time. The authors concluded that slowing down may have provided the time needed to reflect on the hierarchical nature of the DCCS task and to resolve the conflict inherent in the task (Espinet et al., 2012).

Similarly, Moriguchi et al. (2015) trained 3- to 5-year-old preschoolers on the DCCS in two experiments. Children performed a pre-test, training and a post-test. In the experimental group, they interacted with a puppet and were asked to explain the task with all the rules to the puppet, to think about task demands or possible strategies to solve the task in order to foster metacognitive reflection. Results showed that the experimental group improved from pre-test to post-test and performed significantly better than the control group at post-test. Moreover, using NIRS Moriguchi et al. (2015) showed a higher activation in the left PFC after training, again confirming the importance of the PFC for EF.

There is also evidence from task switching: Chevalier and Blaye (2016) investigated whether children's EF monitoring drives EF development from 6 to 10 years of age. They recorded gaze position while participants performed a self-paced task-switching paradigm. In this task, the children had as much time as they needed to proactively prepare for the next task. Both the analysis of gaze trajectories and performance showed that older children were better prepared than younger ones when they responded, even though younger participants could have taken more time to prepare their response. Thus, with increasing age children are better able to monitor EF engagement, pointing to the important contribution of metacognitive processes to EF development.

Even though these findings highlight the importance of metacognition for efficient EF functioning, metacognitive instructions have rarely been applied in cognitive-training research. Unlike many previous training approaches, metacognitive EF training would not aim to enhance the quantity of EF that children can engage, but to change qualitatively how they engage EF as a function of task difficulty (for an example of metacognitive training in reasoning research see

Houdé et al., 2000, 2001). Thus, metacognitive training should facilitate the flexible adaptation to new tasks by training the children to reflect on how to approach them, for instance integrating information about current task demands and past experiences in order to weigh the respective costs (e.g., mental effort) and benefits (e.g., rewards) of available control strategies (cf. Chevalier and Blaye, 2016). Metacognitive training should further encourage performance evaluation, including error detection and feedback processing, all of which are still gradually developing in young children (e.g., Chevalier et al., 2009; Andersen et al., 2014; DuPuis et al., 2014). Given that this metacognitive approach is relatively task-unspecific, it may even support transfer of flexibility training to untrained tasks and abilities. Future studies may want to consider this promising approach when designing new interventions to improve cognitive flexibility (or EF in general).

#### CONCLUSION

Cognitive flexibility develops rapidly during the preschool years and continues to improve across adolescence and young adulthood. Given that EF, and cognitive flexibility in particular, are related to many important life outcomes including academic achievement (e.g., mathematics or reading skills; Yeniad et al., 2013; Titz and Karbach, 2014) and even health status during adulthood (Moffitt et al., 2011), numerous interventions have been designed to improve childhood EF.

Recent training studies provided accumulating evidence for the trainability of cognitive flexibility in early and middle childhood. We illustrated these training effects and also findings on transfer based on studies applying the DCCS and the task-switching paradigm. Training on both tasks has been shown to transfer to other dimensions of EF and to core dimensions of theory of mind, such as false-belief understanding. Importantly, these effects were not only present on the behavioral level but also mirrored by eye-tracking and neuroscientific measures. Given that the mechanisms underlying these training and transfer effects are not fully understood, future studies should try disentangling them, possibly by considering individual differences in training outcomes and by testing the role of metacognitive processes in the plasticity of cognitive flexibility in childhood.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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# Integration of Advance Information about a Forthcoming Task Switch – Evidence from Eye Blink Rates

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We investigated task switching among four tasks by means of a modified cuing procedure with two types of cues. One type of cue consisted of a standard task cue indicating the next task. In half of the trials, this task cue was preceded by another type of cue that reduced the set of candidate tasks from four to two tasks. In addition, we measured participants' spontaneous eye blink rates (EBRs) at the beginning, in the middle, and at the end of the experiment. Whereas interindividual differences in mean EBR had no pronounced effect on task switching performance, changes in EBRs during the first half of the experiment significantly modulated the interaction of the effects of the two types of cues. We suggest that changes in EBRs in the early phase of the experiment reflect adaptations of dopaminergic projections serving to integrate advance information about a forthcoming task switch.

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#### INTRODUCTION

Experiments on task switching aim at elucidating the mechanisms underlying the remarkable human ability to adjust cognition and action according to dynamically changing demands (cf. Kiesel et al., 2010, for a review). On a conceptual level, a certain way of interpreting sensory input and acting accordingly is assumed to be implemented by a particular 'task set,' and a change of the way sensory input is dealt with is assumed to be accompanied by a reconfiguration of the task set. In a typical task switching experiment, changing demands (or 'task switches') are most often induced by presenting external cues signaling the need to adopt a different task set, but they can also be the result of a change in internal conditions or follow an internally represented action plan.

In the vast majority of task switching experiments, switching proceeds among only two tasks. There is also a line of research, devoted to the so-called backward inhibition effect, which for methodological reasons investigates switching among three tasks (cf. Koch et al., 2010). However, there are considerably less studies on switching among four or even more tasks. This neglect of task environments with a larger number of tasks seems to be problematic for several reasons. First, with regard to ecological validity, people are quite often confronted with situations in which more than two action alternatives are available. Second, there is evidence that switching among four tasks exhibits substantial functional differences compared to switching among only two tasks. For example, mere foreknowledge of an upcoming task without explicit cues is much more effective with four as compared to two tasks (e.g., Kleinsorge and Apitzsch, 2012), suggesting that task selection is based on more elaborate task coding in the former as compared to the latter case (cf. Kleinsorge and Scheil, 2015, for details). Third, selection of a certain action often proceeds in a gradual manner, starting from restricting the number of alternative actions to a limited number

of candidate actions followed by choosing among the remaining options. Such a situation was instantiated in the present experiment.

On a neurophysiological level, choosing among candidate actions is intimately linked to processes affected by the neuromodulator dopamine. In this respect, two structures are strongly influenced by dopaminergic projections, the prefrontal cortex (PFC) and the basal ganglia (BG). Both structures are heavily interconnected, but the details of their interplay are far from being completely understood. Regarding the PFC, dopamine is assumed to modulate the balance between robust maintenance of representations in working memory and their flexible updating (e.g., Durstewitz and Seamans, 2008). The updating of working memory representations in PFC is also influenced by the BG that are assumed to provide a 'Go signal' facilitating such an updating (cf. Frank and O'Reilly, 2006). The generation of this Go signal proceeds along a 'direct pathway' that relies mostly on the D1 subtype of dopamine receptors. This direct pathway is complemented by an 'indirect pathway' which relies primarily on D2 receptors. The indirect pathway provides a 'Nogo signal' that suppresses competing responses. Importantly, while higher levels of dopamine provide excitatory input to the direct pathway, facilitating the generation of a Go signal, high levels of dopamine have inhibitory effects on the indirect pathway, thereby weakening the D2-driven tonic inhibition of competing responses.

Evidence suggests that variations in eye blink rates (EBRs) are intimately linked to dopamine-driven cognitive processes, with higher EBRs reflecting more involvement of dopaminergic processing (cf. Jongkees and Colzato, 2016, for a recent review). In this respect, EBRs are probably mainly related to the D2 receptor system of the BG (cf. Groman et al., 2014). According to the 'prepare and select'-model of dopaminergic function in the striatum by Keeler et al. (2014), one key functional distinction between the D1-dominated direct pathway and the D2-dominated indirect pathway consists of the independence vs. competitiveness of action representations within corticostriatal connections: Whereas action representations within the direct pathway are shaped by reward association strength in a rather independent manner, action representations within the indirect pathway are subject to lateral inhibition.

Given that our current understanding strongly suggests a key role for fronto-striatal circuits that are modulated by dopamine in the flexible updating and maintenance of the contents of working memory, and assuming that interindividual differences in EBRs reflect variations in the efficiency of parts of these circuits, it makes sense to expect that performance in task switching experiments should correlate with variations in EBRs. Such an expectation is also corroborated by studies showing that administration of the D2 receptor agonist bromocriptine improves task switching performance, with this improvement being prevented by pretreatment with the D2 receptor antagonist sulpiride (van Holstein et al., 2011). In line with this reasoning, there are studies showing that variations in individual EBR indeed correlate with task switching performance. However, this relationship is not as straightforward as one might wish. The currently best established finding, which was originally reported

by Dreisbach et al. (2005) and subsequently replicated by Müller et al. (2007) as well as Tharp and Pickering (2011), consists of the observation that high EBRs go along with reduced switch costs when a post-switch target stimulus is associated with a previously not presented feature (color) while a to-be ignored stimulus (distractor) is associated with the previous target feature ('perseveration condition'). However, when a post-switch target stimulus is associated with a previously to-be ignored feature while a to-be ignored stimulus is associated with a previously not presented feature ('learned irrelevance condition'), high EBRs go along with increased switch costs, as compared to low EBRs. This interaction might be explained by the assumption that relatively high dopaminergic activity goes along with a novelty bias that aids performance when task-relevant information is associated with a new feature, but impairs performance when the new feature is associated with distracting information (cf. Dreisbach et al., 2005).

While the aforementioned findings strongly suggest an effect of dopaminergic activity on task switching performance driven by novelty, it is quite unusual in typical task switching experiments to associate either relevant or irrelevant information with a novel feature. Rather, in most of these studies all possibly (ir)relevant stimulus features are introduced already from the outset. Typical stimuli in task switching experiments are, for example, letterdigit combinations (e.g., Rogers and Monsell, 1995). During a task switch, letters and digits change their role as targets vs. distractors without any 'new' features serving to facilitate or hinder the performance of a switch. In such a situation, in case of a switch the competition between task relevant and irrelevant routes of information processing has to be resolved by either boosting the activation of the currently relevant or by diminishing the activation of a previously relevant but now irrelevant processing route (or by a combination of both). Both of these processes probably rely in part on dopaminergic projections. Furthermore, as outlined above, the 'prepare and select'-model proposed by Keeler et al. (2014) suggests that while boosting a now-relevant task set may rely more heavily on a D1mediated signal, D2-mediated processes may be more implicated in the competition by now-irrelevant task sets. This assumption provides the rationale of the present study.

In the present experiment, we employed the double-cue procedure originally introduced by Kleinsorge and Scheil (2015). Participants were asked to switch among four tasks. During a single trial, this set of four tasks may or may not be reduced to a set of only two candidate tasks by a first cue (pre-cue). A second cue (task cue) may or may not designate one of the tasks as the relevant one in advance of the onset of the imperative stimulus. Ultimately, the relevant task is indicated by the task cue presented concurrently with the target stimulus. Thus, the experiment was based on a 2 × 2 design in which the first factor determined whether the relevant task was selected among four or two candidate tasks, and the second factor determined whether the relevant task was selected in advance or only after the presentation of the imperative stimulus. (Whether the task was a task repetition or a switch constituted a third factor). The main finding of the original study of Kleinsorge and Scheil (2015) was that reducing the number of candidate tasks from four to two

provided an advantage that affected task switches significantly stronger than task repetitions.

In the present study, we replicated this experiment and measured participants' EBRs in addition. We reasoned that the facilitation of task switches provided by reducing the number of candidate tasks might have been due to a lower updating threshold induced by lower competition among tasks because of a smaller number of competing tasks. According to the 'prepare and select'-model proposed by Keeler et al. (2014), such an effect should be located primarily within the D2-pathway of the BG. Based on the assumption that EBRs primarily reflect the dopaminergic activity within that pathway, we expected to observe significant modulations of the effect of reducing the number of candidate tasks by EBRs. However, due to the complexity of dopaminergic modulations of fronto-striatal circuits, we were reluctant to make specific predictions regarding the precise nature of these correlations. On a behavioral level, we expected to replicate our former observations (Kleinsorge and Scheil, 2015) that both the pre-cue and the task cue would result in pronounced reductions of mean response times and switch costs, with our main interest being focused on the switchcost reducing effect of the pre-cue that reduces the number of candidate tasks from four to two.

#### **MATERIALS AND METHODS**

#### **Participants**

Twenty-one women and 5 men with a mean age of 23.3 years (range: 19–29) participated. All had normal or corrected-to-normal vision (contact lenses were not allowed). The study was approved by the local ethics committee of the Leibniz Research Centre for Working Environment and Human Factors. All participants gave their written informed consent for study participation.

#### **EBR Measurement**

For recoding eye movements, a BrainVision QuickAmp (Brain Products<sup>TM</sup> GmbH, Germany) system with two vertical (one upper, one lower) Ag-AgCl electrodes was used. Participants were comfortably seated in front of a blank poster with a fixation cross at eye level with a distance of about 1 m. They were instructed to look at the cross in a relaxed state without moving their head or activating facial muscles to avoid EOG artifacts. During measurement, the experimenter left the room. As EBR is supposed to be stable during the day but to increase in the evening (08:30 p.m., Barbato et al., 2000), data were not collected after 5 p.m. EBR was measured three times for 6 min each, before the beginning of the task switching experiment (t1), after seven experimental blocks (t2) and at the end of the session (t3). The first measurement was meant to obtain a measure of interindividual EBR differences unaffected by the upcoming task and to provide a baseline for the following measures. Raw measurements were converted to standardized EBRs (blinks/min).

The whole experimental session took place in a windowless room with constant lightning conditions, avoiding dazzling

during EBR measurement as well as screen reflections during the task switching procedure.

#### Stimuli, Tasks, and Apparatus

Imperative stimuli consisted of combinations of one digit from range 1-9 (excluding 5) and one of the letters A, B, E, G, N, O, S, and U. Each stimulus was about 7 mm in height and 4 mm in width. Letters and digits were presented side by side, their position chosen randomly in every trial. Task-relevant stimuli were equally distributed across the tasks, the other (to be ignored) stimulus was chosen at random in every trial. Task cues consisted of a dark blue square, diamond, circle, or triangle surrounding the position of the imperative stimulus with a size of about 70 mm × 70 mm. Participants switched among four tasks. Two of them were numerical judgment tasks, one regarding the magnitude (smaller vs. larger than five) and one regarding the parity of the digits. The magnitude task was indicated by the diamond, the parity task by the circle. In the two letter tasks, letters had to be judged regarding their position in the alphabet (first or second half), indicated by the triangle, or whether it was a vowel or a consonant, indicated by the square. To reduce the set of candidate tasks from four to two, small pre-cues were presented in a row above (square and triangle) and below (circle and diamond) the position of the imperative stimulus with a size of about 15 mm × 15 mm each. Initially, all four pre-cues were colored gray (no reduction of the set of candidate tasks), with two of them turning dark blue in half of the trials (reduction condition).

Stimuli were presented centrally on a 17" monitor on light-gray background. Viewing distance was not restricted but amounted to approximately 60 cm. Responses were made by pressing the 'y'-key of a German QWERTZ-keyboard for small and even digits as well as for vowels and letters from the first half of the alphabet and the '-'-key for large and odd digits, for letters from the second half and for consonants.

#### Task Switching Procedure

At the beginning of the experiment, participants were provided with on-screen instructions in which the tasks and the meaning of the cues were explained. Instructions emphasized speed as well as accuracy. Participants were informed that at the beginning of each trial, the four pre-cues would be visible in gray color above and below the position of the imperative stimulus and that in some trials, two of the pre-cues would turn blue, indicating that one of the two tasks whose pre-cues changed color would be the relevant one in the next trial. Participants were advised to use this information to prepare especially for the two remaining candidate tasks.

The probability of each task to be the relevant one in the next trial was 0.25, which corresponds to an overall repetition proportion of 0.25 (cf. Kleinsorge and Scheil, 2015, Exp. 2). In half of the trials, no pre-cue was presented, meaning that no tasks could be excluded because none of the cues symbolizing each of the four tasks changed color. For the other trials, two of the cues turned blue and remained so for 1,500 ms. This change of color provided the pre-cue. Pre-cues indicated each combination of two candidate tasks with equal probability. Thus, the pre-cue

increased the probability of two of the tasks to 0.50. Pre-cues were shown until the presentation of the task cue. For the task cue, two CTIs (cue-target intervals) of 0 and 800 ms were employed. That is, the task cue could either be presented in advance or concurrently with the imperative stimulus. The duration of the CTI was evenly and pseudo-randomly distributed across the tasks and across the two levels of pre-cue presentation. The responsestimulus interval (RSI) was set to 2,500 ms. In case of an error, error feedback was presented for additional 1,000 ms; in case of reaction times (RTs) slower than the RT deadline of 2,500 ms, RT feedback was presented for additional 1,000 ms. Stimuli and task cue remained visible until the participant's reaction or until RT deadline was reached. The experiment consisted of 14 blocks of 96 trials each. [A more detailed description can be found in Kleinsorge and Scheil (2015)]. Between the blocks, participants were allowed to rest and to continue the experiment in a selfpaced manner in order to minimize fatigue effects. The whole session lasted for about 2 h.

#### **RESULTS**

The analysis of the data proceeded in several steps. In a first step, mean individual RTs and error rates (ERs) were analyzed as a function of Pre-Cue (no pre-cue vs. pre-cue), CTI (0 vs. 800 ms), and Task Transition (repetition vs. switch). Then, we analyzed mean individual EBRs during the course of the experiment. Subsequently, we augmented the preceding analyses by including additional between-participants factors representing interindividual differences in EBRs. Specifically, we subdivided our sample of participants by median splits computed on the basis of (a) initial EBRs measured at the beginning of the experiment (EBRt1), (b) changes of EBRs during the first half of the experiment (EBRt1 - EBRt2), and (c) changes of EBRs during the second half of the experiment (EBRt2 - EBRt3). Whereas initial EBRs were taken as a measure of overall interindividual differences in dopamine level, changes of EBRs across phases of the experiment were taken as measures of interindividual differences in adapting to the task in terms of dopamine responses. Changes between Phases 1 and 2 should reflect mainly functional adaptations in terms of dealing with (certain aspects of) the task, whereas changes between Phases 2 and 3 probably also reflect processes of saturation and fatigue.

#### **Overall Analyses of Task Performance**

The ANOVA of mean individual RTs as a function of Pre-Cue (no pre-cue vs. pre-cue), CTI (0 vs. 800 ms), and Task Transition (repetition vs. switch) yielded significant main effects of all factors (cf. **Table 1**). The presentation of a pre-cue that reduced the number of candidate tasks from four to two decreased RT from 1,041 ms to 982 ms, F(1,25) = 86.66, MSe = 2,119,  $\eta_p^2 = 0.78$ . A CTI of 800 ms decreased RT to 802 ms, as compared to a CTI of 0 ms (1,222 ms), F(1,25) = 661.71, MSe = 13,852,  $\eta_p^2 = 0.96$ . Task switches went along with a mean RT of 1,072 ms, as compared to 951 ms with task repetitions, F(1,25) = 86.50, MSe = 8,859,  $\eta_p^2 = 0.78$ . All main effects were significant at p < 0.001.

Decreasing the number of candidate tasks from four to two decreased switch costs from 145 to 98 ms, F(1,25) = 22.80, MSe = 1,275, p < 0.001,  $\eta_p^2 = 0.48$ . Despite the tremendous benefit that the presentation of a task cue provided with respect to mean RT, mean switch costs were lower with a CTI of 0 ms (108 ms) as compared to a CTI of 800 ms (134 ms), F(1,25) = 5.71, MSe = 1,605, p < 0.05,  $\eta_p^2 = 0.19$ . As revealed by a significant interaction of Pre-Cue, CTI, and Task Transition, F(1,25) = 7.06, MSe = 1,110, p < 0.05,  $\eta_p^2 = 0.22$ , this increase of switch costs by an increase of the CTI was confined to conditions with only two candidate tasks. When there was no pre-cue that restricted the number of candidate tasks, switch costs were nearly the same for conditions with a CTI of 0 ms (145 ms) and 800 ms (146 ms). However, when a pre-cue reduced the number of candidate tasks from four to two, a CTI of 0 ms was associated with a switch cost of 72 ms, which increased to 123 ms with a CTI of 800 ms.

The corresponding ANOVA of ERs only yielded significant main effects of all three factors. A reduction of the number of candidate tasks from four to two decreased ER from 7.5 to 6.6%, F(1,25)=13.06, MSe = 0.00035, p<0.01,  $\eta_p^2=.34$ . A CTI of 0 ms was associated with a mean ER of 8.2%, as compared to a mean ER of 5.9% with a CTI of 800 ms, F(1,25)=52.55, MSe = 0.00052, p<0.01,  $\eta_p^2=0.68$ . Task switches increased ER to 8.0%, as compared to an ER of 6.0% with task repetitions, F(1,25)=10.12, MSe = 0.0022, p<0.01,  $\eta_p^2=0.29$ .

As can be seen from **Table 1**, there was no hint that the performance data were compromised by speed-accuracy tradeoffs.

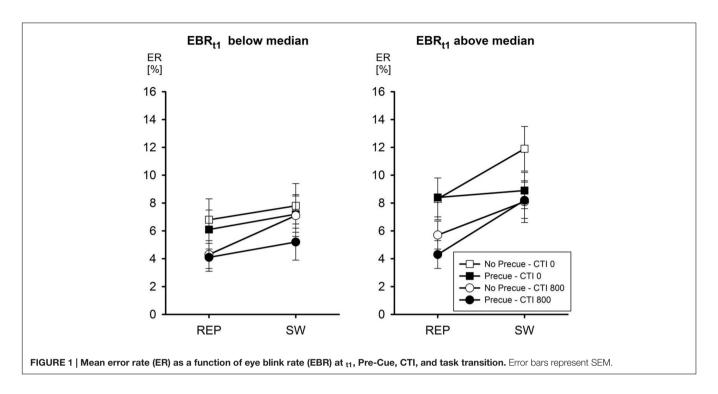
#### **Analysis of EBRs**

Mean EBRs (blinks per minute) amounted to 19.87 (SD: 13.13) at t1, to 21.72 (SD: 14.14) at t2, and to 24.17 (SD: 13.89) at t3. The increase of EBRs during the course of the experiment was significant, F(2,50) = 5.05, MSe = 24.01, p < 0.05,  $\eta_p^2 = 0.17$ . Newman–Keuls *post hoc* tests revealed that EBRs at t1 differed significantly from EBRs at t3 (p < 0.01), whereas the difference between t1 and t2 was not significant (p > 0.15). The difference between t2 and t3 was marginally significant (p < 0.08).

TABLE 1 | Mean reaction times (RT) (ms) and error rate (ER) (%) as a function of pre-cue (no presentation vs. presentation of a pre-cue), CTI (0 ms vs. 800 ms), and task transition (Repetition vs. Switch).

	No p	re-cue	With		
	CTI 0 ms	CTI 800 ms	CTI 0 ms	CTI 800 ms	М
RT					
Task repetition	1184 (26)	753 (29)	1151 (28)	716 (25)	951 (25)
Task switch	1329 (28)	899 (30)	1223 (29)	839 (30)	1072 (27)
M	1257 (26)	826 (28)	1187 (28)	777 (27)	
ER					
Task repetition	7.5 (1.0)	5.0 (0.7)	7.3 (1.0)	4.2 (0.7)	6.0 (0.8)
Task switch	9.8 (1.2)	7.6 (1.0)	8.0 (0.9)	6.7 (0.9)	8.0 (1.0)
М	8.7 (1.0)	6.3 (0.7)	7.6 (0.9)	5.5 (0.7)	

SEM are given in parentheses.



Individual EBRs were highly intercorrelated, with *r*'s ranging between 0.82 (t1, t3) and 0.92 (t2, t3).

## Analyses of Task Performance Including Individual Differences in EBRs EBRs at 11

Subdividing our sample of participants according to their EBRs at t1 by a median split (median: 18.08) and entering this between-participants factor Initial EBR into the analyses of RTs and ERs as a function of Pre-Cue (no pre-cue vs. pre-cue), CTI (0 vs. 800 ms), and Task Transition (repetition vs. switch) yielded no significant interactions including the factor Initial EBR in the analysis of RTs (all p's > 0.25). <sup>1</sup>

In the analysis of ERs, however, Initial EBR entered into a significant third-order interaction of all four factors, F(1,24) = 8.73, MSe = 0.0004, p < 0.01,  $\eta_p^2 = 0.27$ . This interaction is depicted in **Figure 1**. In line with the main focus of the present study, we interpret this interaction regarding the effect of decreasing the number of candidate tasks from four to two, that is, the effect of Pre-Cue. For participants with an Initial EBR below the median, the presentation of a pre-cue had only a negligible effect on ERs. Only with a CTI of 800 ms there was a tendency that the reduction of the number of tasks decreased switch costs (from 2.7 to 1.1%), but this was statistically not

significant (all p's > 0.15 according to Newman–Keuls *post hoc* tests). In contrast, for participants with an Initial EBR above the median the presentation of a pre-cue significantly reduced the ER associated with a task switch from 12.0 to 8.9 with a CTI of 0 ms, p < 0.001, but not with a CTI of 800 ms (p > 0.8). Pre-Cue did not affect ERs with task repetitions at any level of CTI (p's > 0.25).

#### EBRt1 - EBRt2

In a next step, we replaced the between-participants factor Initial EBR by a factor based on the individual differences in EBRs between t1 and t2. Specifically, we subtracted for each participant the EBR measured at t2 from the EBR measured at t1, and subsequently subdivided our sample by a median split according to this difference (Median: -1.29). Thus, there was a median increase of mean EBR from t1 to t2 of 1.29 blinks per minute. Note that the split of our sample along the median is almost identical to a split in terms of an absolute increase vs. decrease of EBRs across the two times of measurement. In fact, the latter way of splitting participants into subgroups would have resulted in only one participant being assigned to another group, with this difference having no substantial effect on our main results. The differences EBRt1 – EBRt2 correlated only weakly with the EBRs measured at t1 (r = 0.21, n.s.).

Entering the between-participants factor  $EBR_{t1}$  –  $EBR_{t2}$  into the analyses of RTs and ERs as a function of Pre-Cue (no pre-cue vs. pre-cue), CTI (0 vs. 800 ms), and Task Transition (repetition vs. switch) yielded the following picture (cf. **Table 2**). In the analysis of RTs, the only significant interaction involving  $EBR_{t1}$  –  $EBR_{t2}$  was the third-order interaction of all four factors, F(1,24) = 8.2, MSe = 862, p < 0.01,  $\eta_p^2 = 0.25$ . This interaction is depicted in **Figure 2**. This interaction is based on the observation that the second-order interaction Pre-Cue × CTI × Task

<sup>&</sup>lt;sup>1</sup>The use of median splits has sometimes been criticized for a loss of information and/or a higher risk of statistical errors. However, as shown by Iacobucci et al. (2015a,b), these concerns are most often unwarranted when a single variable based on a median split is combined with orthogonal experimental variations that are uncorrelated with the median-split based factor. Furthermore, our study is based on the replication of a complex factorial design that lends itself to an analysis based on ANOVA in a straightforward manner, which in this case also facilitates the communication of the results as compared to regression-based approaches.

TABLE 2 | Mean RT (ms) and ER (%) as a function of EBR<sub>T1-T2</sub> (below vs. above median), pre-cue (no presentation vs. presentation of a pre-cue), CTI (0 ms vs. 800 ms), and task transition (Repetition vs. Switch).

		EBR <sub>T1-T2</sub> below median			EBR <sub>T1-T2</sub> above median				
		No pre-cue		With pre-cue		No pre-cue		With pre-cue	
		CTI 0 ms	CTI 800 ms	CTI 0 ms	CTI 800 ms	CTI 0 ms	CTI 800 ms	CTI 0 ms	CTI 800 ms
RT	Task repetition	1141 (36)	688 (38)	1090 (36)	674 (34)	1228 (36)	819 (38)	1211 (36)	757 (34)
	Task switch	1283 (38)	865 (42)	1186 (41)	807 (42)	1374 (38)	934 (42)	1260 (41)	871 (42)
	M	1212 (35)	776 (38)	1138 (37)	741 (37)	1301 (35)	876 (38)	1236 (37)	814 (37)
ER	Task repetition	8.8 (1.4)	4.4 (1.0)	7.3 (1.4)	4.7 (1.0)	6.2 (1.4)	5.6 (1.0)	7.2 (1.4)	3.7 (1.0)
	Task switch	10.1 (1.7)	8.0 (1.5)	8.0 (1.4)	7.4 (1.3)	9.5 (1.7)	7.2 (1.5)	8.0 (1.4)	6.0 (1.3)
	М	9.5 (1.4)	6.2 (1.0)	7.7 (1.3)	6.1 (1.0)	7.9 (1.4)	6.4 (1.1)	7.6 (1.3)	4.9 (1.0)

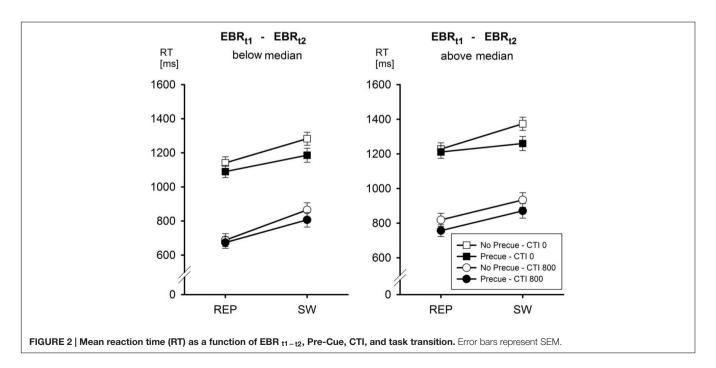
SFM are given in parentheses

Transition was significant [F(1,12) = 17.85, MSe = 834, p < 0.01, $\eta_p^2 = 0.60$ ] only in the group of participants with a EBR<sub>t1</sub> – EBR<sub>t2</sub> difference above the median, that is, for participants tending to decrease their EBR in the first half of the experiment. In contrast, in the group of participants with an EBRt1 - EBRt2 difference below the median this interaction was far from significant, F < 1. Newman–Keuls *post hoc* tests indicated that this pattern was due to the fact that in the group of participants with a  $EBR_{t1} - EBR_{t2}$ difference above the median, reducing the number of candidate tasks from four to two reduced switch costs only with a CTI of 0 ms (from 146 to 49 ms, p < 0.001), but not with a CTI of 800 ms (switch costs 115 vs. 114 ms with no pre-cue vs. pre-cue). In contrast, in the group of participants with a EBRt1 - EBRt2 difference below the median, switch costs were reduced by the Pre-Cue both with a CTI of 0 ms (142 vs. 95 ms, p < 0.05) and with a CTI of 800 ms (177 vs. 133 ms, p < 0.05).

In the corresponding analysis of ERs, the only interaction involving the between-participants factor EBRt1 - EBRt2 was the second-order interaction  $EBR_{t1}$  –  $EBR_{t2}$  × Pre-Cue × CTI, F(1,24) = 8.37, MSe = 0.00035, p < 0.01,  $\eta_p^2 = 0.26$ . This interaction was due to the fact that in the group of participants with a EBR<sub>t1</sub> - EBR<sub>t2</sub> difference below the median, reducing the number of candidate tasks reduced ER more with a CTI of 0 ms (from 9.5 to 7.7%) than with a CTI of 800 ms (from 6.2 to 6.1%). In the group of participants with an EBR<sub>t1</sub> - EBR<sub>t2</sub> difference above the median, this pattern was reversed (7.9 vs. 7.6% with CTI 0, 6.4 vs. 4.9% with CTI 800).

#### EBRt2 - EBRt3

In a final step, we replaced the between-participants factor based on the individual differences in EBRs between t1 and t2 by a factor based on a median split of the individual differences in EBRs between t2 and t3 (Median: -0.96). As with the median split regarding the differences in EBRs between t1 and t2, this median is close to zero. Splitting participants into subgroups in terms of an absolute increase vs. decrease of EBRs across the two



times of measurement would have resulted in two participants being assigned to another group, with this difference having no substantial effect on our main results The differences  $EBR_{t2}$  –  $EBR_{t3}$  correlated only weakly with the differences  $EBR_{t1}$  –  $EBR_{t2}$  (r=-0.17, n.s.).

Entering the new between-participants factor  $EBR_{t2} - EBR_{t3}$  into the analysis of RTs yielded only one significant interaction involving  $EBR_{t2} - EBR_{t3}$ . This was the interaction  $EBR_{t2} - EBR_{t3} \times CTI$ , F(1,24) = 4.95, MSe = 11,960, p < 0.05,  $\eta_p^2 = 0.17$ . This was based on the observation that the reduction of RTs induced by a CTI of 800 ms was more pronounced in the group with a  $EBR_{t2} - EBR_{t3}$  difference below the median (1,191 vs. 737 ms), as compared to the group with a  $EBR_{t2} - EBR_{t3}$  difference above the median (1,253 vs. 867 ms). The corresponding analysis of ERs yielded no significant interaction involving  $EBR_{t2} - EBR_{t3}$ , all p's > 0.12.

#### **DISCUSSION**

The results of the present study can be summarized as follows. First, apart from replicating basic task switching effects (switch costs, effect of CTI), we replicated the main finding of Kleinsorge and Scheil (2015). We again observed that the presentation of a pre-cue that reduced the number of candidate tasks from four to two mainly affected task switches and therefore reduced switch costs substantially. One deviation from the original findings of Kleinsorge and Scheil (2015) consists of the observation of a significant second-order interaction of Pre-Cue, CTI, and Task Transition in the present study. However, as will be discussed below, the observation of this interaction was restricted to a subgroup of participants of the present study and not observed in another subgroup.

Coming to the effects of interindividual variations of EBRs on task switching performance with the current double-cue paradigm, overall differences in EBRs as measured at the beginning of the experiment had only a minor effect that was restricted to accuracy. Specifically, our observations suggest that participants with an initial EBR above the median were better able to use the pre-cue to increase accuracy, with this effect being restricted to task switches with CTI of 0 ms. This finding is in line with the assumption that higher baseline levels of dopamine facilitate task switching (cf. Jongkees and Colzato, 2016). Furthermore, it seems that one specific process being facilitated by relatively high levels of dopamine is the restriction of the repertoire of candidate actions in line with dynamically changing situational demands, perhaps by adjusting the relative amount of lateral inhibition among action alternatives.

Whereas the effect of overall differences in EBRs on task performance was rather restricted under the current conditions, changes of EBR during the first part of the experiment had a more tremendous impact. In particular, participants who tended to increase their EBR when dealing with the task made use of the pre-cue irrespective of the level of CTI, whereas participants who tended to decrease their EBR seemed to follow a more disjunctive strategy in that the effects of the pre-cue were different

when a task cue was available than when it was not<sup>2</sup>. With no task cue (CTI = 0), the presentation of a pre-cue affected task switches much more than task repetitions, whereas with a task cue task repetitions and switches were affected by the pre-cue to the same degree. This observation suggests that for this group of participants, the strategy of using the pre-cue was influenced by the presentation of a task cue, which happened after encoding of the precue should have taken place. A possible explanation for this somewhat counterintuitive assumption relates to the temporal features of the different trial types. Specifically, trials in which both types of cue information were presented in advance are characterized by an onset of the pre-cue only 200 ms after the beginning of the trial. That is, if the initial display changes immediately after trial onset, participants can infer that in this trial, not only a pre-cue but also a task cue will be presented. This could have led participants to use the information of the pre-cue only superficially and to rely to a larger degree on the information given by the task cue. In contrast, if nothing happens immediately after trial onset, participants are not able to distinguish between the other three conditions in advance. This seems to be a methodological shortcoming, however, the alternative solution would have been a longer presentation of the pre-cue in trials with a CTI of 0 ms, which would have resulted in a confound of both intervals or, alternatively, the use of different intertrial intervals which also would have conveyed predictive information about the upcoming cuing procedure. In any case, it seems that differences in the change of EBRs while adapting to the task were associated with different strategies of cue use, with participants tending to decrease their EBR being more focused on the task cue that unambiguously specified the upcoming task.

Kleinsorge and Scheil (2015) interpreted the switch-cost reducing effect of the pre-cue in terms of a change in the way a task is selected. Specifically, we proposed that a selection among only two candidate tasks is facilitated by an establishment of antagonistic constraints among the two tasks that enables task selection based on any perceptually available feature that discriminates between the two tasks. This is possible because any evidence favoring one of the tasks is at the same time evidence against the other task. In contrast, when selecting one of four tasks, evidence against one of the tasks does not directly translate into evidence in favor of one of the remaining three candidate tasks. This line of reasoning converges upon the assumption that the effect of the pre-cue is brought about by enhancing inhibition among competing tasks, a process that is probably implemented by the striatal D2 system (cf. Keeler et al., 2014). Based on the assumption that an increase of EBRs reflects increased reliance on D2 mediated processing (cf. Jongkees and Colzato, 2016), observing a more consistent effect of the precue across levels of CTI in the subgroup of participants with

 $<sup>^2</sup>$ When analyzing this pattern in terms of correlations, we observed a positive correlation of  $r=0.36\ (p<0.08)$  between the individual differences in EBR changes between t1 and t2 and the reduction of switch costs as a function of the precue with a CTI of 0 ms, but a negative correlation of  $r=-0.37\ (p<0.07)$  between these measures with a CTI of 800 ms. While these observations corroborate our conclusion that the interaction of the effects of the two types of cues was modulated by changes in EBRs, we think that a selective comparison of single correlations across particular factorial combinations within our rather complex experimental design provides no comprehensive analytical strategy to capture our main findings.

a  $EBR_{t1}$  –  $EBR_{t2}$  difference below the median (indicating an increased EBR) therefore makes sense. In particular, it seems that these participants consistently exploited the pre-cue to adjust the level of inter-task competition in a way that facilitated task switching induced by the task cue.

In contrast, participants who tended to decrease their EBR during the first part of the experiment (EBR $_{t1}$  – EBR $_{t2}$  difference above the median) exhibited a pre-cue induced reduction of switch costs only when no task cue was presented. This suggests that when a task cue was (expected to be) available, these participants selected the relevant task in a more 'direct' manner (possibly more reliant on D1 mediated processing) that was less reliant on inhibitory connections among competing tasks. In this case, the task cue may directly trigger the retrieval of the task with the strongest reward association, which is likely to be the currently relevant one.

Of course, at present the foregoing considerations are in large part speculative. However, we find it remarkable that the EBR-based effects we observed concern mainly the effects of pre-cue, that is, the experimental variation that we supposed to be susceptible to D2 mediated interindividual variation on a priori grounds, as outlined in the introduction. What is somewhat surprising is the observation of EBR-related effects mainly in terms of changes of EBRs rather than their overall level. This suggests that changes in EBRs may constitute an as long neglected marker of interindividual differences in adapting to tasks demands that place a burden on processes of task (or action) selection. At present, changes in EBRs are mainly considered as markers of fatigue (EBR increase, cf. Barbato et al., 2007; McIntire et al., 2014). When measured on-task, EBR decreases and blink suppression are positively correlated with task difficulty (cf. Oh et al., 2012; Wascher et al., 2015). However, our measure of EBR changes as a function of adaptation to task demands lies somewhere between the more global measures of state-dependent EBR changes as indictors of fatigue and the temporarily more fine-grained measures of blink suppression

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during more demanding phases of task performance. To the best of our knowledge, our study is the first to provide evidence that EBR changes in a time range of about 1 h are predictive of a very specific aspect of processing in a task switching context, namely the use of foreknowledge that allows for a proactive restriction of the number of alternative task options. Of course, this novelty of our results implies also a need for replication of this kind of relationship.

Overall, our findings support the assumption of an intimate link between dopaminergically modulated processes and cognitive flexibility. Although the intricacies of this link are only beginning to be understood, the double-cue procedure employed in the present experiment promises to serve as a tool to distinguish between control processes related to task switching that are differentially affected by different (possibly D1 vs. D2 mediated) dopaminergic projections. On a functional level, these processes may differ with respect to the degree by which they rely on inhibition among competing tasks (like an implementation of antagonistic constraints) vs. direct activation of a particular task based on the availability of an unambiguous task cue.

#### **AUTHOR CONTRIBUTIONS**

TK and JS designed the experiment, analyzed the data, and wrote the article.

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# More than Attentional Tuning – Investigating the Mechanisms Underlying Practice Gains and Preparation in Task Switching

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In task switching, participants perform trials of task repetitions (i.e., the same task is executed in consecutive trials) and task switches (i.e., different tasks are executed in consecutive trials) and the longer reaction times in switch trials in comparison to these times in repetition trials are referred to as switch costs. These costs are reduced by lengthening of an interval following a cue that indicates the upcoming task; this effect demonstrated effective task preparation. To investigate the role of task switching practice for these preparation effects and task switch costs, we applied a task switching paradigm, involving two digit classification tasks, in six successive practice sessions and varied the length of the preparation interval. To further examine practice-related processing alterations on preparation, particularly concerning the focusing of visual attention and control of response competition, we added an Eriksen flanker task in the initial and the final session. Unlike the two digit tasks, which were always validly cued, the Eriksen flanker task occurred randomly after a cue that indicated one of the other two tasks (i.e., invalid task cuing). The results showed that, in the initial session, task switch costs for the digit tasks were reduced after a long preparation interval but this reduction disappeared after practice. This finding is consistent with the assumption of practice-related enhancement of preparation efficiency concerning nonperceptual task processes. Flanker interference was larger after preparation for a task repetition than for a task switch and (regarding error rates) larger in the final than in the initial session. Possible mechanisms underlying these attentional modulations evoked by task-sequence-dependent preparation and by task switching practice are discussed.

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#### INTRODUCTION

To investigate cognitive flexibility, researchers often apply task switching situations. In these situations, participants execute two different tasks in varying sequences, usually on the same set of target stimuli. These tasks are frequently afforded by distinctly different perceptual dimensions thereof, such as when participants switch between a shape classification and a color classification when presented with colored geometrical shapes. In the *task-cuing procedure*, the two tasks are presented in random order and participants are informed about the identity of the upcoming task by a cue that precedes or accompanies the presentation of the target stimulus (e.g., Meiran, 1996). Switching between tasks (i.e., executing a different task than on the directly preceding trial) incurs a cost in reaction times (RTs) and sometimes error rates in comparison to task repetitions

(i.e., executing the same task on successive trials). These costs are referred to as (*task*) *switch costs* (overview in Monsell, 2003; Kiesel et al., 2010; Vandierendonck et al., 2010).

#### TASK PREPARATION

Because participants are informed about the identity of the upcoming task by the task cue, a manipulation of the length of the cue-target interval (CTI) produces different amounts of processing time for task-specific preparation. Performance usually benefits from an increase of the CTI, more so on task switch trials in comparison to repetition trials, resulting in a reduction of the switch costs (e.g., Meiran, 1996). This reduction at long in contrast to short CTIs has been referred to as the *Reduction In Switch Cost (RISC) Effect* (Liefooghe et al., 2009).

The RISC Effect in the task-cuing procedure has been accounted for in terms of more effective task preparation in task switch trials, suggesting some form of advance task-set reconfiguration not necessary in task repetition trials (Rogers and Monsell, 1995). Although various suggestions have been made regarding specific components of this reconfiguration (for an overview, see Kiesel et al., 2010), little consensus has been reached so far. However, a coarse distinction can be made concerning preparatory attentional weighting of perceptual dimensions (i.e., biasing processing toward the target stimulus dimension of the upcoming task, e.g., Meiran, 2000; see also Müller et al., 2003; Lien et al., 2010) and preparation of nonperceptual task processes, such as increasing the readiness of the application of task-specific stimulus-response transformation rules (e.g., Mayr and Kliegl, 2000). Whereas attentional weighting may facilitate performance in case the component tasks are associated with distinct perceptual target dimensions (e.g., color vs. shape classification tasks), non-perceptual preparation may also be applied in such situations. Therefore, preparation effects observed when tasks are associated with different stimulus dimensions, are ambiguous regarding a perceptual vs. nonperceptual preparation locus.

In contrast, attentional weighting cannot be applied when the component tasks are not afforded by different perceptual target dimensions. A frequently implemented example of the latter situation involves switching between purely semantic classification tasks, such as when participants judge the magnitude vs. the parity of stimulus digits (e.g., Sudevan and Taylor, 1987; Schuch and Koch, 2003; Kiesel et al., 2007). Because performance benefits when the CTI is increased (i.e., the RISC Effect occurs) in such situations (e.g., Schuch and Koch, 2003) it can be concluded that task-specific preparation is not confined to re-adjustment of attentional weights assigned to perceptual dimensions, but rather to preparation of non-perceptual task processes.

#### TASK SWITCHING PRACTICE

Several studies have demonstrated that switch costs are reduced with practice distributed over two or more experimental sessions

(Rogers and Monsell, 1995; Kray and Lindenberger, 2000; Cepeda et al., 2001; Kray and Eppinger, 2006; Karbach and Kray, 2009; Zinke et al., 2012) with some studies showing an extreme reduction of such costs to (still statistically significant) 6, 8, or 20 ms (Berryhill and Hughes, 2009; Strobach et al., 2012). In some studies, the reduction of switch costs after practice occurred under conditions of comparably short preparation intervals (e.g., Rogers and Monsell, 1995; Meiran et al., 2000; Minear and Shah, 2008), indicating that the practice-related facilitation of processing in switch trials does not depend on time-consuming preparatory processes. Extending these findings, Meiran et al. (2000) observed a three-way interaction involving trial type (i.e., task repetition vs. task switch), preparation interval (i.e., CTI), and practice, reflecting a practice-induced reduction of the RISC Effect. That is, switch costs were larger in trials associated with a short than with a long preparation interval in the first session but less so in the second session (see Meiran, 1996, for a similar finding, obtained during the course of a single experimental session). In a study of Cepeda et al. (2001), the reduction of the RISC Effect after practice failed to reach statistical significance but a significant reduction of the preparation benefit in task switch trials compared to (repetition) trials from single-task blocks (i.e., blocks with only one component task) was found. A plausible explanation of these practice findings is to assume that task switching practice results in enhanced efficiency of task (switch) preparation (i.e., less time needed to achieve a prepared state after practice). Because in the study of Meiran et al. (2000) no analogous effect was observed regarding the interval between the response in one trial and the task cue in the following trial, task switching practice does not seem to result in speed-up passive decay of the previously applied task-set.

Noteworthy, in both studies, Meiran et al. (2000) and Cepeda et al. (2001), participants switched between tasks that differed regarding their perceptual target dimensions. More precisely, in Meiran et al.'s study, participants judged the vertical vs. horizontal displacement of a stimulus in a 2 X 2 grid, whereas in Cepeda et al.'s study participants were presented strings of repetitive digits (e.g., 333, 3333, 22, or 2222) and were either required to count the number of or to identify the elementary digits. Task preparation effects in these previous studies may thus be brought about by perceptual preparation. That is, task switching practice may have resulted in a speedup of preparatory re-adjustment of attentional weights given to the upcoming task's stimulus dimension, leaving other taskspecific mental operations unaffected. Such attentional biasing may constitute a powerful means of task selection (e.g., Meiran et al., 2008). On the other hand, it does not provide an universal method of dealing with alternative task demands as it can only be applied when the tasks to-be-switched are associated with differing perceptual stimulus dimensions. In the current study, we aimed to extend previous findings to the preparation of non-perceptual task processes. To this end, we provided participants with task switching practice of six sessions for a combination of tasks (i.e., magnitude vs. parity judgements) that were not associated with perceptually different stimulus dimensions, and varied the preparation interval (i.e., CTI).

A second indication of interference between task-sets, in addition to the switch costs, is usually observed when the tasks switched between involve the same set of stimuli and motor responses. In that case, stimuli can be categorized depending on whether they afford the same motor response in both tasks or whether they afford different responses, referred to as congruent and incongruent, respectively. For illustration, consider switching between parity and magnitude judgments with a left-sided key press response to indicate that the stimulus digit is odd or smaller than 5 and a right-sided key press response to indicate that the stimulus digit is even or larger than 5. With such an arrangement the digit 3 would be congruent (i.e., left key responses in magnitude and parity judgment tasks) whereas the digit 7 would be incongruent (i.e., right key response in magnitude judgment task and left key response in parity judgment task). Congruency effects, that is, worse performance in trials involving incongruent compared to congruent stimuli, as observed in many studies (e.g., Rogers and Monsell, 1995; Meiran, 1996; Kiesel et al., 2007), thus reflect some kind of application of the stimulus-response translation rules of the irrelevant task to the current stimulus (Meiran and Kessler, 2008; Wendt and Kiesel, 2008). Interestingly, contrasting with task switch costs, congruency effects are often not reduced when the CTI is increased (e.g., Rogers and Monsell, 1995; Meiran, 1996), suggesting that increased preparation is not associated with enhanced shielding of task performance against this form of task interference. In the current study, we used overlapping sets of stimuli and responses which allowed us to examine the role of extended practice on task preparation and congruency effects.

In addition to assessing performance after practice in the practiced tasks we employed a probe task method to investigate possible practice-related alterations in task preparation. Specifically, we intermixed trials of a third task which was not presented in the practice sessions. This (probe) task involved a different set of stimuli and occurred with equal probability after a cue indicating the magnitude or parity judgment tasks. In such situations, processing of the probe task should suffer from malpreparation (i.e., from preparation for the task invalidly indicated by the cue, e.g., Hübner et al., 2004; Wendt et al., 2012), thus more advanced task preparation might evidence itself in modulated performance in probe task trials. More specifically, assuming that longer CTIs are used for more advanced task-set reconfiguration one would expect a disadvantage of probe task performance after longer CTIs, and assuming that task switching practice results in a speed-up of task-set reconfiguration processes during preparation, a similar disadvantage should emerge after a short CTI.

This probe task method offers the opportunity to investigate specific aspects of processing characteristics by choosing a probe task that is associated with well-established and well-understood behavioral effects. Modulations of these effects by task switching practice may reveal specific processes or representations affected by the practice experience. As a first step in this direction, we used an Eriksen flanker task (Eriksen and Eriksen, 1974) as probe task. This task is widely considered diagnostic for the occurrence of competition between response representations evoked by the target stimulus and by surrounding irrelevant stimuli, referred to

as flankers (e.g., Gratton et al., 1992; overview in Eriksen, 1995). Intermixing trials of this probe task thus allowed us to assess the degree of response competition evoked by irrelevant stimuli in an unexpected task as a function of task preparation in various conditions of the task switching context (i.e., task repetition and task switch, short and long CTI, before and after practice). Because the resulting strength of response competition is thought to depend on a set of perceptual-cognitive processes, collectively referred to as selective attention, differences in the response competition effect may be informative about the attentional set in these situations. We will consider more specific suggestions regarding the underlying attentional processes in the Section "Discussion."

In summary, the current study was designed to investigate the effect of task switching practice on non-perceptual processes of task preparation. To this end, we conceptually replicated experiments of Meiran et al. (2000) and Cepeda et al. (2001) using a combination of tasks that did not differ regarding their perceptual dimensions. Assuming that task switching practice results in a speed-up of (non-perceptual) task preparation, we expected to observe a practice-related reduction of the RISC effect. In addition, we explored practice effects of task preparation on task representations by presenting an unexpected probe task that allowed us to assess attentional aspects of stimulusresponse processing (i.e., variations in the degree of response competition evoked in an unexpected flanker task). From a broader perspective, the current practice study thus investigates flexible action selection according to one's current task goal, a hallmark of executive functioning, and it's plasticity to the effects of practice (e.g., Karbach and Verhaeghen, 2014; Strobach et al.,

#### MATERIALS AND METHODS

#### **Participants**

Twenty students of the Medical School Hamburg (17 female) participated in the experiment in exchange for course credit. They ranged in age from 21 to 31 years. All participants had normal or corrected to normal vision by self-report.

#### **Apparatus and Stimuli**

Stimulus presentation and RT measurement were performed with a PC. The digits 1 to 9 except 5 were used as stimuli for the magnitude and the parity task. They were displayed on a 22" monitor with a refresh rate of 60 Hz, viewed from a distance of about 60 cm. All digits were presented in white color on a black background, in the center of the screen. The digits extended 0.6 cm (approximately 0.6°) vertically and from 0.3 to 0.4 cm horizontally (approximately 0.6°), presented disks with a diameter of 0.6 cm (approximately 0.6°), presented in the center of the screen, were used as task cues. A blue disk indicated the magnitude task, and a red disk indicated the parity task. On flanker task trials, three arrows, extending in the horizontal dimension, were presented. One of the arrows (i.e., the target) was presented in the center of the screen, whereas the other two arrows (i.e., the flankers) surrounded the central

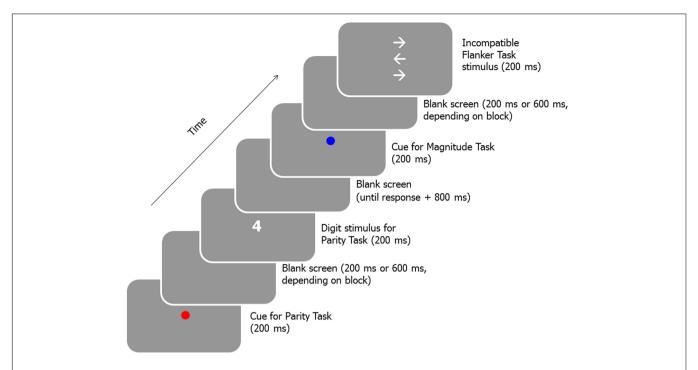


FIGURE 1 | Schematic of a sequence of a Parity task trial and a Flanker task trial (cued as a magnitude trial) of the experimental blocks of the initial and the final session.

arrow symmetrically in the vertical dimension. (All three arrows were horizontally aligned.). The two flanker arrows of a trial always pointed into the same direction and either in the same direction as the target arrow (i.e., compatible) or in the opposite direction as the target arrow (i.e., incompatible). A target-flanker ensemble extended 1.3 cm (approximately 1.2°) vertically and 0.7 cm (approximately 0.7°) horizontally.

Responses were given by pressing the Y key (left) and the M key (right) on a standard QWERTZ-keyboard. Participants pressed the response keys with the index fingers of their left and right hand. In the magnitude task, participants pressed the left key to indicate smaller than 5 and the right key to indicate larger than 5. In the parity task, participants pressed the left key to indicate even and the right key to indicate odd. In the flanker task, participants pressed the left key and right key to indicate that the target arrow pointed to the left and the right, respectively.

#### **Procedure**

There were six experimental sessions. One of the participants failed to attend the final session. The interval between two consecutive sessions ranged from 1 to 6 days (mean: 2.63 days). The initial and the final session were structurally identical. In these sessions, participants first received a practice block of 16 flanker task trials. Then, a practice block involving 48 trials of the magnitude and parity task was administered. A third practice block included trials of all three tasks (16 trials of the magnitude and parity task, each, and 8 flanker task trials). A fourth practice block was structurally identical to the subsequent experimental blocks. This block was composed of 96 trials (32 trials of each of the three tasks). On each trial, the task was chosen randomly

without replacement and the stimulus was chosen randomly, without replacement, out of the set of possible stimuli of the current task. Flanker task trials were presented with a cue indicating the magnitude task or the parity task with equal probability. Each task cue, digit, and target-flanker ensemble were presented in the center of the screen and displayed for 200 ms. The CTI was set to 800 ms in the practice blocks (with the exception of the first practice block, in which no cues were presented). In the experimental blocks the CTI alternated between 400 and 800 ms from block to block, starting with a 400 ms block. In case of a correct response, the cue of the subsequent trial occurred 800 ms after the response. In case of an incorrect response the message "FALSCHE ANTWORT" (incorrect response) was displayed after a delay of 500 ms in white color for 1000 ms. In case no response was given within 5600 ms (in blocks with a short CTI of 400 ms) or 5200 ms (in blocks with a long CTI of 800 ms) the message "ZU LANGSAM" (too slow) was displayed in white color for 1000 ms. In both cases, the cue of the subsequent trial occurred 800 ms after the offset of the feedback. Figure 1 displays a schematic of a sequence of trials. Instructions stressed to respond as quickly as possible while attempting to achieve a high level of accuracy. Nine experimental blocks were administered. Between blocks, the participants were allowed to rest for some time.

The training sessions (Sessions 2–5) were identical to the initial and final sessions with the following exceptions. In these sessions the participants were administered only the magnitude task and the parity task. On each trial, each of the two tasks occurred with equal probability and the target digit was chosen randomly from the set of possible digits. Two practice blocks

involved 32 trials each (CTI = 800 ms). Then, 10 blocks of 64 trials each were administered. The CTI alternated between 400 and 800 ms from block to block, starting with 800 ms.

#### **RESULTS**

Reaction time and accuracy data of the experimental blocks of the initial and the final session were subjected to statistical analyses. For these analyses, data from the practice blocks, from the first trial of each block, from trials following a flanker task trial, from trials with stimulus repetitions (i.e., the same digit stimulus in the preceding and current trial), and from trials following a trial associated with an incorrect response (i.e., post-errors) were discarded from all analyses. The RT analyses were based only on data from trials with correct responses.

#### **Digit Tasks**

Although our research questions focused on comparisons of performance patterns in the initial session and the final session, we also present the mean RTs and mean error proportions of the digit task trials from the training sessions (i.e., Sessions 2–5). These data are displayed in **Table 1**.

Figure 2 displays the results obtained in trials associated with the digit tasks in the initial and final sessions. Analyses of Variance (ANOVAs) with repeated measures on the factors Session (initial vs. final), Task Sequence (repetition vs. switch), CTI (400 ms vs. 800 ms), Congruency (congruent vs. incongruent), and Response Sequence (repetition, switch)<sup>1</sup> were conducted on the mean RTs and proportions of correct responses. Regarding RTs, there were significant main effects of Session, Task Sequence, and Congruency, F(1,18) = 20.7,  $p < 0.01, \, \eta_p^2 = 0.535, \, F(1,18) = 35.5, \, p < 0.01, \, \eta_p^2 = 0.664,$ and F(1,18) = 103.2, p < 0.01,  $\eta_p^2 = 0.851$ , respectively, indicating that responding was slower in the first session than in the final session, slower on task switch trials than on task repetition trials, and slower in incongruent than in congruent trials (i.e., congruency effect). CTI and Congruency interacted, F(1,18) = 4.7, p < 0.05,  $\eta_p^2 = 0.20$ , indicating that the congruency effect tended to be larger with the long CTI (see **Figure 2**). Further, switch costs were smaller in the final session than in the initial session, F(1,18) = 7.3, p < 0.05,  $\eta_p^2 = 0.288$ . This was modulated, however, by a three-way interaction with CTI, F(1,18) = 6.5, p < 0.05,  $\eta_p^2 = 0.267$ , which indicated that the practice-induced reduction of switch costs was confined to the short CTI condition, resulting in the disappearance of the RISC Effect in the final session (see **Figure 2**). Task Sequence also interacted with Response Sequence, F(1,18) = 46.1, p < 0.01,  $\eta_p^2 = 0.719$ , indicating that response repetitions were faster than response switches in task repetition trials but slower in task switch trials. This was further modulated by an interaction with Session, F(1,18) = 4.7, p < 0.05,  $\eta_p^2 = 0.206$ , because the response repetition disadvantage in task switch trials was reduced in the final session.

The analysis of response accuracy yielded significant main effects of Task Sequence and Congruency, F(1,18) = 18.7, p < 0.01,  $\eta_p^2 = 0.510$ , and F(1,18) = 60.7, p < 0.01,  $\eta_p^2 = 0.771$ , respectively, indicating task switch costs and a congruency effect, respectively. Both these factors interacted, F(1,18) = 19.6, p < 0.01,  $\eta_p^2 = 0.521$ , reflecting a larger congruency effect in task switch trials than in task repetition trials. Furthermore, Response Sequence interacted with Task Sequence, F(1,18) = 38.4, p < 0.01,  $\eta_p^2 = 0.681$ , indicating that response repetitions were more error-prone than response switches in task repetition trials versus task switch trials. Response Sequence also interacted with Congruency, F(1,18) = 15.0, p < 0.01,  $\eta_p^2 = 0.455$ , and these three factors (i.e., Response Sequence, Task Sequence, and Congruency) resulted in a significant three-way interaction, F(1,18) = 34.9, p < 0.01,  $\eta_p^2 = 0.660$ . This was because the congruency effect was larger with response repetition trials when the task repeated and larger with response switches when the task switched.

Further, we conducted a control analysis which compared the effects of the task sequence and the CTI for the fifth and the sixth (i.e., final) session, because intermixing trials of the flanker task at the end of practice may have affected processing of the digit tasks in an unknown way, e.g., the probability to switch to a particular digit task was changed from 0.50 to 0.33. (Assuming that practice effects in the digit tasks may have reached an asymptotic level before the final session, a difference in practice between these two sessions can be considered negligible, thus allowing us to attribute any performance difference to the presence vs. absence of flanker task trials.) An ANOVA with

TABLE 1 | Mean reaction times (in ms)/mean error percentages (in parentheses: standard deviations) of the digit categorization tasks as a function of session (2–5), task sequence (task repetition vs. task switch), and cue-target interval (CTI: 400 ms vs. 800 ms).

	Task R	epetition	Task Switch		
	CTI = 400 ms	CTI = 800 ms	CTI = 400 ms	CTI = 800 ms	
Session 2	581 (91)/5.1 (4.6)	600 (119)/5.2 (4.1)	643 (124)/7.0 (5.5)	648 (147)/6.9 (6.2)	
Session 3	552 (88)/4.5 (4.4)	600 (125)/5.6 (4.1)	613 (131)/7.8 (6.1)	629 (143)/6.8 (6.1)	
Session 4	518 (65)/5.3 (3.6)	551 (84)/5.6 (4.9)	574 (94)/7.8 (7.4)	593 (109)/7.9 (6.0)	
Session 5	548 (83)/5.3 (4.1)	579 (105)/6.0 (6.1)	597 (96)/8.2 (6.9)	622 (144)/7.8 (7.0)	

CTI, cue-target interval.

<sup>&</sup>lt;sup>1</sup>Previous studies, using the same set of responses for both tasks, have yielded a robust interaction of the sequence of responses on consecutive trials with the sequence of tasks. More specifically, whereas task repetitions tend to be facilitated by repetition of the response, the opposite pattern is often found in task switch trials (e.g., Rogers and Monsell, 1995; Meiran, 1996).

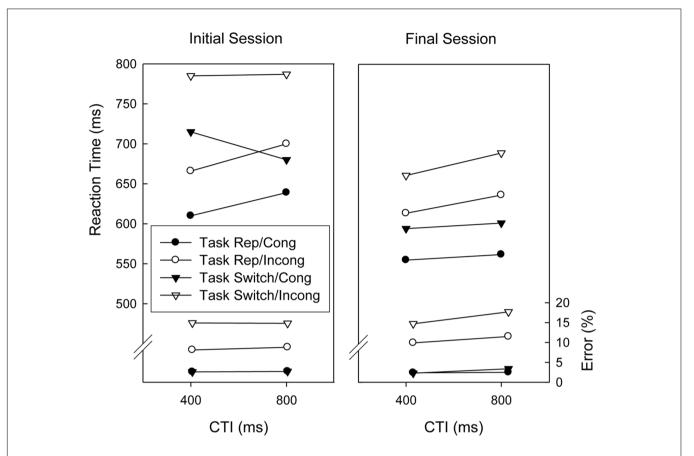


FIGURE 2 | Mean reaction times and error percentages of the digit categorization tasks before and after extended practice (i.e., initial session and final session) as a function of task sequence, cue-target interval (CTI), and congruency. Task Rep, Task Repetition; Cong, Congruent stimulus; Incong, Incongruent stimulus.

repeated measures on the factors Session (fifth vs. sixth/final), Task Sequence (repetition vs. switch), and CTI (400 ms vs. 800 ms), conducted on the mean RTs, yielded only significant main effects of Task Sequence,  $F(1,18)=27.4,\ p<0.01,\ \eta_p^2=0.604,$  and CTI,  $F(1,18)=9.9,\ p<0.01,\ \eta_p^2=0.355,$  indicating switch costs and a general disadvantage when the CTI was long, respectively. The corresponding ANOVA of response accuracy yielded only significant main effects of Task Sequence,  $F(1,18)=13.0,\ p<0.01,\ \eta_p^2=0.420,$  and Session,  $F(1,18)=6.5,\ p<0.05,\ \eta_p^2=0.266,$  indicating switch costs and generally less accurate performance in the final session, respectively. Thus, this data set shows no evidence that the introduction of the Flanker task at the end of practice affects task switching between the digit tasks.

#### Flanker Task

**Figure 3** displays the results obtained in trials associated with the flanker task. ANOVAs with repeated measures on the factors Session (initial vs. final), Cue Sequence (repetition vs. switch), Flanker Compatibility (compatible vs. incompatible), CTI (400 ms vs. 800 ms), and Response Sequence (repetition, switch) were conducted on the mean RTs and proportions of correct responses of trials involving the flanker task. Note that

a cue repetition invalidly indicates a task repetition whereas a cue switch invalidly indicates a task switch. Regarding RTs, there were significant main effects of Session, Flanker Compatibility, and CTI, F(1,18)=30.8, p<0.01,  $\eta_p^2=0.631$ , F(1,18)=58.1, p<0.01,  $\eta_p^2=0.764$ , and F(1,18)=17.1, p<0.01,  $\eta_p^2=0.487$ , respectively, indicating that responding was slower in the initial session than in the final session, slower in incompatible trials than in compatible trials, and slower in the long CTI condition than in the short CTI condition. The only other significant effect was the two-way interaction of Cue Sequence and Flanker Compatibility, F(1,18)=6.0, p<0.05,  $\eta_p^2=0.251$ , reflecting that the Flanker compatibility effect was larger when the cue indicated a task repetition than when it indicated a task switch.

The corresponding analysis of response accuracy yielded a significant main effect of Flanker Compatibility, F(1,18)=21.2, p<0.01,  $\eta_p^2=0.541$ , indicating that responses were more error-prone in incompatible trials than in compatible trials. This congruency effect was larger in the final session than in the initial session, indicated by a significant two-way interaction of Flanker Compatibility and Session, F(1,18)=6.4, p<0.05,  $\eta_p^2=0.263$ . There were also two significant four-way interactions (Session × Cue Sequence × Flanker Compatibility × Response sequence, F(1,18)=4.9, p<0.05,  $\eta_p^2=0.214$ , and Cue

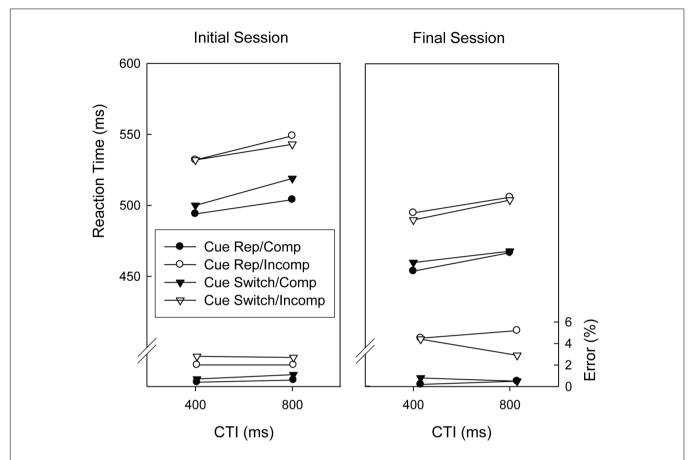


FIGURE 3 | Mean reaction times and error percentages of the Eriksen flanker task before and after extended practice (i.e., initial session and final session) as a function of cue sequence, flanker compatibility, and cue-target interval (CTI). Cue Rep, Cue Repetition; Comp, Compatible stimulus; Incomp, Incompatible stimulus.

Sequence × Flanker Compatibility × CTI × Response Sequence, F(1,18) = 5.8, p < 0.05,  $\eta_p^2 = 0.245$ ) which were not further discussed, however<sup>2</sup>.

#### DISCUSSION

The current study aimed at pursuing effects of extended practice on task switching performance, focusing on the optimization of processes of task preparation. In particular, we set out to investigate the occurrence of a previously reported reduction of the RISC Effect after practice (Meiran et al., 2000; see also Cepeda et al., 2001). This investigation extends the assessment of a speedup of preparation for a task switch under conditions in which task preparation cannot be based on shifting attention toward

the perceptual target dimension of the upcoming task, but this switch can be rather based on non-perceptual processes of task preparation.

Performance in the (practiced) digit tasks displayed a monotone trend of RT improvement until the fourth session (see **Table 1**). It thus seems that testing in the sixth session took place under conditions of asymptotic practice benefit. There was also a pronounced improvement for the flanker task despite the fact that this task received no practice during Sessions 2 to 5. Although it can, logically, not be dismissed that the benefit for the flanker task in the final session was brought about by practicing flanker task trials during the initial session (i.e., a test–retest effect; e.g., Green et al., 2014), it is also possible that the higher degree of practice in the other tasks improved the capability of dealing with the occurrence of an unexpected (i.e., invalidly cued) task.

The reduction of the RISC Effect previously reported by Meiran et al. (2000) and—when comparing task switch trials and trials from single-task blocks—Cepeda et al. (2001) was clearly replicated. Given that the tasks with which participants practiced switching in the current study were not associated with perceptually different target dimensions, this finding cannot be attributed to accelerated preparatory shifting of attention toward the stimulus dimension of the upcoming task but must

 $<sup>^2</sup>$ In an additional analysis, we replaced the factor Response Sequence by the factor Congruency on the Preceding Trial, thus checking for influences of preceding (task) conflict conditions on the flanker compatibility effect. No such influence was found in neither the ANOVA on RTs nor on response accuracy, since none of these analyses revealed two-way interactions of Flanker Compatibility and Congruency on the Preceding Trial as well as no significant higher-order interactions involving these two factors (Fs < 1). These null findings add to a considerable number of studies suggesting domain-specific mechanisms of attentional adjustment to conflict conditions (overview in Egner, 2008).

be ascribed to a different component of task-set reconfiguration. It is also worth noting that the reduction of the RISC Effect occurred under conditions of a stimulus set that was twice as large (i.e., eight individual digits) as the stimulus set used by Meiran et al. (2000), demonstrating that the practice-related reduction of the RISC Effect is not confined to very small stimulus sets for which it might be conceivable that increased practice results in a shift from executing different tasks to executing individual stimulus–response translations.

Contrasting with the task switch costs, the congruency effect was not affected by practice, suggesting that task switching practice does not lead to enhanced shielding of task processing from interference exerted by the set of the competitor task. Replicating previous studies (e.g., Rogers and Monsell, 1995; Meiran, 1996) the congruency effect was neither reduced by an increase in preparation time. In fact, in the current study it tended to be larger when the CTI was long.

To gain additional insight into the processing changes brought about by extended task switching practice, we analyzed performance in the flanker task after short and long CTIs (i.e., after preparation for one of the digit tasks). As expected on the assumption of larger malpreparation during a longer CTI, flanker task RTs were generally larger when the CTI was long. The fact that this response slowing after a long CTI was not reduced in the final session seems to cast some doubt on our hypothesis of speeded-up task preparation. If such a speed-up occurred, one might expect that a strong degree of malpreparation would be achieved even after a short CTI, thereby reducing the processing advantage in short CTI trials. It is interesting to note, however, that a general slowing in trials associated with a long CTI also occurred in the digit tasks from Session 2 on (see Table 1). Indeed, our additional ANOVA conducted on data of digit task trials from the prefinal and the final sessions (i.e., Sessions 5 and 6, respectively), yielded a significant effect of slower responses when the CTI was long. In light of these findings it seems possible that the expected reduction of response slowing after a long CTI in flanker task trials of the final session was masked by some general (i.e., task-unspecific) slowing.

Flanker compatibility effects were larger when the cue indicated a task repetition (i.e., when the cue matched the previous task and cue) than when the cue indicated a task switch. Various processes have been suggested to account for an increase in flanker interference in different experimental contexts, including, for instance, less selective spatial attention (e.g., Eriksen, 1995), increased spared stimulus processing capacity (and obligatory allocation thereof to the flankers, Lavie, 1995), or increased general response readiness at the time of stimulus presentation (Correa et al., 2010). Although we can only speculate about the precise mechanisms underlying the effect of "executed task-cued task sequence" on the flanker compatibility effect, we would like to point out that it might be linked to recent modeling work of task switching. Specifically, applying diffusion models to task switching performance both Karayanidis et al. (2009) and Schmitz and Voss (2012) found evidence consistent with a lowering of response caution during preparation for a

task repetition as compared to a task switch. Given that reduced response caution is liable to increase the relative weight of flanker information (e.g., Gratton et al., 1992), such adjustment might also explain the increase in flanker interference after preparation for a task repetition found in the current study.

Regarding error rates, flanker interference was generally larger in the final session than in the initial session, suggesting the occurrence of more pronounced (susceptibility to) response conflict after task switching practice. Like the unclear role of practice for malpreparation of the probe task, this practice-related increase of susceptibility to irrelevant stimulus objects deserves further investigation.

In general, the present findings are consistent with the literature on practice effects on cognitive control and executive functions, such as working memory updating and dual tasking. In fact, practice demonstrated increased efficiency to update information in working memory. Among others, this increased efficiency is related to an increase in the working memory capacity (e.g., Olesen et al., 2004; Dahlin et al., 2008). In the context of dual tasking, improved executive control functions were related to improved attention allocation between tasks (e.g., Kramer et al., 1995) and attention control skills (e.g., Strobach et al., 2014).

In summary, the current study provides novel evidence for the assumption that task switching practice elicits a speed-up of preparation of non-perceptual processes of task-set reconfiguration. Intermixing trials of a probe task appears to be a useful tool to pinpoint specific components of task processing affected by an experimental intervention, such as practice. Preliminary findings obtained in this study are consistent with the notions of lowered response caution when preparing a task repetition and generally enhanced susceptibility to stimulus-induced conflict after task switching practice.

#### **ETHICS STATEMENT**

This study was carried out in accordance with the recommendations of the Declaration of Helsinki of the World Medical Association and approved by the Ethics Committee of the German Psychological Society (Ethik-Kommission der Deutschen Gesellschaft für Psychologie). Informed written consent was obtained from all participants prior to participation.

#### **AUTHOR CONTRIBUTIONS**

MW and TS planned the experiment and wrote the article. SK programmed the experimental protocol, collected the data, and analyzed the data.

#### **ACKNOWLEDGMENT**

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### Task Dominance Determines Backward Inhibition in Task Switching

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Switching between tasks is assumed to be accompanied by inhibiting currently irrelevant, but competing tasks. A dominant task that strongly interferes with performing a weaker task may receive especially strong inhibition. We tested this prediction by letting participants switch among three tasks that differ in dominance: a location discrimination task with strong stimulus-response bindings (responding with lefthand and right-hand button presses to stimuli presented left or right to the fixation cross) was combined with a color/pattern and a shape discrimination task, for which stimulus-response mappings were arbitrary (e.g., left-hand button press mapped to a red stimulus). Across three experiments, the dominance of the location task was documented by faster and more accurate responses than in the other tasks. This even held for incompatible stimulus-response mappings (i.e., right-hand response to a left-presented stimulus and vice versa), indicating that set-level compatibility (i.e., "dimension overlap") was sufficient for making this location task dominant. As a behavioral marker for backward inhibition, we utilized n-2 repetition costs that are defined by higher reaction times for a switch back to a just abandoned and thus just inhibited task (ABA sequence) than for a switch to a less recently inhibited task (CBA, n-2 non-repetition). Reliable n-2 task repetition costs were obtained for all three tasks. Importantly, these costs were largest for the location task, suggesting that inhibition indeed was stronger for the dominant task. This finding adds to other evidence that the amount of inhibition is adjusted in a context-sensitive way.

Keywords: task switching, backward inhibition, n-2 task repetition costs, stimulus-response compatibility, task dominance

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#### **INTRODUCTION**

Many everyday-life situations require the coordination of different tasks and goals. In this regard, the task-switching paradigm has become a popular tool to study those processes that enable the flexible adjustment to changing task requirements. In a typical task-switching experiment, participants switch between two (or more) tasks, which usually goes along with costs, that is, response times (RTs) and often also error rates are higher when a switch from one task to the other is required than when the task stays the same across consecutive trials. These switch costs indicate that switching even between simple tasks is not trivial and seems to require time-consuming control processes that enable cognitive flexibility (for reviews, see Kiesel et al., 2010; Vandierendonck et al., 2010).

What exactly are the mechanisms that enable flexible switching from one task to another? It is now widely accepted that part of the switch costs reflect processing demands involved in changing/updating task-specific configurations or task sets (e.g., Rogers and Monsell, 1995; Meiran, 1996), but also that proactive interference from previous settings (or task-set inertia as termed by Allport et al., 1994), contributes to the switch costs as well (e.g., Goschke, 2000; for review see Kiesel et al., 2010; Vandierendonck et al., 2010). Therefore, besides reconfiguring the system to new task requirements, "getting rid" of previous configurational settings likely also plays a role. One mechanism thought to facilitate flexible switching is inhibition: strong competitor tasks or tasks that were relevant previously constitute a source of interference and task-set carry-over. Inhibiting these competitor tasks reduces conflict and enables one to efficiently perform the currently relevant task (Mayr and Keele, 2000; see Koch et al., 2010, for a review).

The role of inhibiting or suppressing no longer relevant task sets is addressed in many theories and accounts on task switching (see Koch et al., 2010, for a review). For instance, Allport et al. (1994) suggested that when performing a task, the tendency to perform a no longer relevant and competing task needs to be suppressed or inhibited (see also e.g., Goschke, 2000). Moreover, Mayr and Keele (2000) proposed a hypothetical mechanism termed "backward inhibition" that functions as "... a counterforce to the persistent-activation property of control settings and would thus "clear the slate" for currently relevant task sets" (Mayr and Keele, 2000, p. 5). The research question we address in the present paper is whether the amount of inhibition is adjusted to the degree of automatization of a task and the influence (conflict) a task exerts on other tasks.

First evidence that inhibition plays a role in task switching comes from a finding known as switch-cost asymmetry. At the same time, asymmetric switch costs also indicate that some tasks need to be inhibited more strongly than other ones. Allport et al. (1994) observed that switch costs are higher when participants switch to the stronger, more dominant task of a pair of tasks. For instance, when participants switch between reading the word and naming the print color of incongruent color-word Stroop stimuli (e.g., the word "red" printed in green color), switch costs are higher for word reading than for color naming. Within the task-set inertia account, this, at first glance, counterintuitive effect has been interpreted in terms of inhibition: To enable performing the weaker, color-naming task the competing, normally dominant word-reading task must be actively suppressed. When a switch is now required from color naming to word reading, residual inhibition should still be present, which hampers the reactivation and/or processing of the word-reading task. Similar asymmetric switch costs have been observed for language switching in bilingual naming tasks (i.e., larger costs for switching back to the dominant of two languages, see, e.g., Meuter and Allport, 1999; Philipp et al., 2007; see Declerck and Philipp, 2015, for a review). However, the theoretical conclusiveness of such asymmetrical switch costs with respect to an underlying inhibitory mechanism remains debatable (see Koch et al., 2010; Gade et al., 2014; Declerck et al., 2015, for discussion).

Today the least controversial and widely accepted way to test inhibition in sequential task control is the assessment of n-2 task repetition costs (Mayr and Keele, 2000; see Koch et al., 2010, for a review). In this variant of the task-switching paradigm, participants switch among three tasks. The basic idea is that when switching to a new task is mediated by inhibiting no-longer relevant tasks, switching back to a just abandoned task should result in decreased performance, because inhibition persists over time and this residual inhibition needs to be overcome. The typical finding is that RTs are slower when returning to a recently abandoned task (e.g., as in ABA compared to CBA sequences). These n-2 repetition costs have been replicated many times and are to date robust against alternative interpretations (see Koch et al., 2010, for review). They, therefore, represent a widely accepted empirical marker for inhibition.

There is already some evidence that n-2 repetition costs are sensitive to the degree of task competition. For example, Schuch and Koch (2003) used a go/no-go variation and found that previous tasks are only inhibited if the current task requires a response (i.e., go trial) but not if it turned out to be a nogo trial. Moreover, Gade and Koch (2007) manipulated the representational overlap of the response sets across the tasks and found that n-2 repetition costs were largest if there was full overlap of response sets across all tasks. In another study, Gade and Koch (2005) manipulated the intertrial interval (specifically, they varied the response-cue interval in cued task switching) and found that n-2 repetition costs were largest if the preceding interval was very short, suggesting that strong residual activation of the preceding task triggers stronger backward inhibition. Finally, in language-switching studies larger n−2 repetition costs were observed for the dominant, first language (e.g., Philipp et al., 2007; Declerck et al., 2015).

Since in research on task switching it is common practice to aggregate across tasks, evidence regarding the relation between the dominance pattern of the tasks included in a switching situation and the mechanisms applied to control the impact of each task is rather scarce. Specifically, apart from languageswitching studies, in which performance is typically examined for each language separately, there is hardly any evidence for the modulation of n-2 repetition costs by task dominance. One notable exception is the study of Arbuthnott (2008). She examined switching among three different digit-categorization tasks that vary in difficulty. Participants judged whether a given digit was larger or smaller than 5 (easy), odd or even (easy/intermediate), or a prime number or not (hard). In two experiments, involving either separate or overlapping response sets, larger n-2 repetition costs were observed for the easier of two tasks than for the harder one. However, this pattern was significant only in the first experiment and only if the tasks with the greatest difference in difficulty were compared, so that it cannot be considered as confirmed that the amount of inhibition targeted against an unwanted task specifically depends on the amount of competition this particular task exerts. In the present study, we, therefore, systematically manipulated task dominance and assessed n-2 repetition costs as behavioral marker for inhibitory processes separately for each task across a series of three experiments.

Backward Inhibition and Task Dominance

Task dominance was manipulated by introducing a task with high spatial stimulus-response (S-R) compatibility (Kornblum et al., 1990). In this location task, the participants responded with left or right button presses to objects presented left or right to the fixation cross. According to the taxonomy of Kornblum et al. (1990), this task is characterized by overlap between the relevant stimulus dimension and the response dimension - the spatial position - and, accordingly, should be performed particularly easily, so that we consider it dominant in the context of the two other tasks. Specifically, this location task was combined with two other tasks, for which stimulus and response dimensions did not overlap (i.e., to indicate the color or the shape of a stimulus with a lateralized response). Because there was no dimensional S-R overlap for these tasks, any mapping of a stimulus to a response was arbitrary, so that there should be no automatic response activation.

With this set of tasks, we assumed that with multidimensional stimuli (i.e., varying in location, color, and shape), efficient performance in a less dominant task may only be possible by inhibiting the dominant location task, because otherwise the spatial location of the stimulus would automatically activate its corresponding response. As a result, switching to the dominant location task should be impaired because of residual inhibition. A similar degree of inhibition might not be necessary for the two other tasks. If the more dominant location task indeed needs to be inhibited more strongly to efficiently perform the less dominant color and shape tasks, then n-2 repetition costs should be larger for the location task than for the other tasks.

#### **EXPERIMENT 1**

#### **Materials and Methods**

#### **Participants**

Twenty students of the RWTH Aachen University (16 female, 4 male) participated. All participants reported having normal or corrected-to-normal vision, and were naïve with respect to the purpose of the study. Mean age was 21.5 years (age range 18–28 years).

This study (experiments 1–3) was carried out in accordance with the ethical guidelines of the German Psychological Society (Deutsche Gesellschaft für Psychologie) with written informed consent from all subjects. Ethical review and approval was not required for this study in accordance with the national and institutional guidelines. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

#### Stimuli, Task, and Procedure

The stimulus material consisted of visually presented multivalent objects that varied on three different dimensions with two values each: location (presented to the left or right side of the screen), color (red or blue), and shape (circle or square). Stimuli were presented on a black screen. The circles had a diameter of 2.25 cm and the squares a side length of 2 cm. Viewing distance was approximately 60 cm.

Participants had to switch among the location, color, and shape tasks. A cue presented in advance indicated the relevant

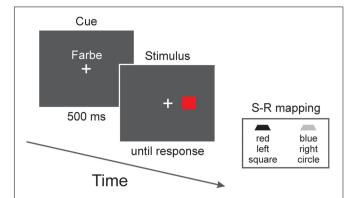


FIGURE 1 | Stimulus sequence of a trial. The cue presented in advance indicated the relevant stimulus dimension. In this example, color is relevant (as indicated by the German word "Farbe" which means color) and, according to the stimulus–response (S–R) mapping (shown is one out of eight possible mappings), the correct response is a left-button press. Note that for the location task, only compatible S–R mappings were used in Experiments 1 and 2 and only incompatible mappings were used in Experiment 3. Furthermore, for Experiments 2 and 3 the color task was replaced by a pattern task (i.e., objects were filled with either horizontal or vertical black/white lines).

dimension (see **Figure 1**). These cues consisted of the German words "Ort" (location) for the location task, "Farbe" (color) for the color task, and "Typ" (type) for the shape task<sup>1</sup>. The cues were presented in white color slightly above the fixation cross. Font was Arial and height was 2 cm.

Each trial started with the presentation of the task cue for 500 ms. The stimulus directly followed the cue (cue-stimulus interval thus was 500 ms). The stimulus remained on the screen until the participant responded (speed as well as accuracy were stressed in the instruction). Feedback was immediately provided after an error (the German word "falsch," which means wrong, was presented for 500 ms). The intertrial interval was 500 ms.

Participants responded by pressing one of two response keys (the two "Alt" keys located to the left and right of the space bar). With two values for each of the three tasks, eight different mappings were possible (e.g., circle, red, and left mapped to the left hand and square, blue, and right mapped to the right hand). In Experiment 1, we only implemented those four mappings that contained the compatible S–R mapping for the location task, that is, for the location task, all subjects responded with a left hand press when the stimulus was presented left and with a right hand press when the stimulus was presented on the right. The mappings were fully counterbalanced across participants.

The experimental session started with a practice block containing 32 trials. The main part consisted of eight blocks with 96 trials each (plus two block-starting trials). Tasks switched in pseudorandom order such that each trial was a switch trial and ABA and CBA sequences occurred equally often for each task within a block. Stimuli were also assigned pseudorandomly, that is, within a block each stimulus occurred equally often in the context of each task–sequence combination and direct stimulus

<sup>&</sup>lt;sup>1</sup>Note that we used the word "Typ" (type) instead of the perhaps more catchy word "Form" (form) for indicating the shape task. This was done to make the differentiation from the color-task indicating cue "Farbe" (color) easier.

repetitions from one trial to the next were omitted (n-2 stimulus repetitions, however, were allowed). Blocks were separated by short breaks in which feedback about the total number of errors in the completed block was provided.

#### Design

Independent variables were the task in the current trial n, which was location, color, or type, and the task sequence which was either of the sort of n-2 repetitions (ABA) or n-2 switches (CBA). Accordingly, we ran analyses of variance (ANOVAs) with these two independent variables on RTs and error rates. F statistics were Greenhouse-Geisser-corrected. The uncorrected degrees of freedom, the corrected p-value, and the respective GG- $\varepsilon$  values are reported. In the first step, we report the findings of the main effect of task in order to address the issue of task dominance. In the second step, we address inhibition and potential differences in the amount of inhibition across the three different tasks by means of the main effect of sequence and the interaction Task  $\times$  Sequence. Besides the raw n-2 repetition costs (the RT difference between ABA and CBA sequences), we also calculated proportional scores (by taking performance in the CBA sequences as baseline) to account for differences in absolute RTs across the tasks.

#### **Results and Discussion**

The first two trials of each block were removed. Trials with RTs shorter than 200 ms or above three standard deviations of a participant's mean in each task were defined as outliers and excluded from the analyses. For RTs, only correct trials were analyzed. Moreover, only trials, in which the correct response was given in the two previous trials, were included in the analyses of RTs and error rates.

#### **Task Dominance**

The upper panel in **Figure 2** shows mean RTs for correct responses in the different tasks and transition sequences. As can be seen, RTs differed substantially across the tasks. This was confirmed by the main effect of task, F(2,38)=66.35, MSE=4,540, p<0.0001,  $GG-\varepsilon=0.911$ . With an average RT of 572 ms, the location task was processed significantly faster than the color and shape tasks with 620 and 740 ms, respectively,  $ps \le 0.001$ . A similar pattern was observed for the error rates: the ANOVA yielded a main effect of task, F(2,38)=5.22, MSE=8.98, p=0.0155,  $GG-\varepsilon=0.819$ . Error rates in the location task amounted to 2.10% and were smaller than in the color task with 3.71% and the shape task with 4.16%, with ps=0.0590 and 0.0049. This overall pattern indicates that our experimental manipulation worked and provides evidence for the dominance of the location task over the other two tasks.

#### **Backward Inhibition**

Response times were smaller in ABA than in CBA sequences, replicating the typical n-2 repetition costs. The main effect of sequence was significant, F(1,19)=40.56, MSE=463, p<0.0001. Regarding the main question in our study, that is, whether these costs are larger for the most dominant task, n-2 repetition costs indeed turned out numerically larger in

the location than in the other two tasks. When we scale the difference scores (to take the huge RT differences into account when interpreting the size of the n-2 repetition costs), the 29-ms effect in the location task is equivalent to a 5.24% RT increase in the ABA compared to CBA sequences. In the other two tasks, the effects correspond with 20 and 26 ms to increases of 2.95 and 3.89%, respectively (see lower panel of **Figure 2**). Although this pattern overall meets our expectations, the interaction Task × Sequence was not significant, F < 1. This also holds when the proportional scores were compared across the three different tasks, F(2,38) = 1.13, MSE = 27, p = 0.3340,  $GG - \varepsilon = 0.780$ .

Sequence had no reliable effect on the error rates. Neither the main effect nor the interaction was significant (Fs < 1).

One reason for the small and not significant differences in the size of the n-2 repetition costs might be that the effect of the dominance manipulation was not strong enough. As can be seen from **Figure 2**, RTs were also relatively small for the color task, which also significantly differed from the most difficult task, the shape task (p < 0.05). Moreover, 6 out of the 20 participants even did not show shorter RTs for the location than for the color task. Thus, the advantage of the location over the color task is not very clear. In Experiment 2, we, therefore, replaced the color task by a more difficult task to see if we can replicate the ordinal pattern of task inhibition effects in a more pronounced manner than in Experiment 1.

#### **EXPERIMENT 2**

#### **Materials and Methods**

#### **Participants**

Data were collected from 20 new participants of the same student population as in Experiment 1. One participant was excluded because of very slow responses (RT > 3000 ms in most of the trials) and, therefore, another new participant was run in exchange. The final sample comprised data of 9 women and 11 men. Mean age was 23.8 years (age range 19–30 years).

#### Stimuli, Task, and Procedure

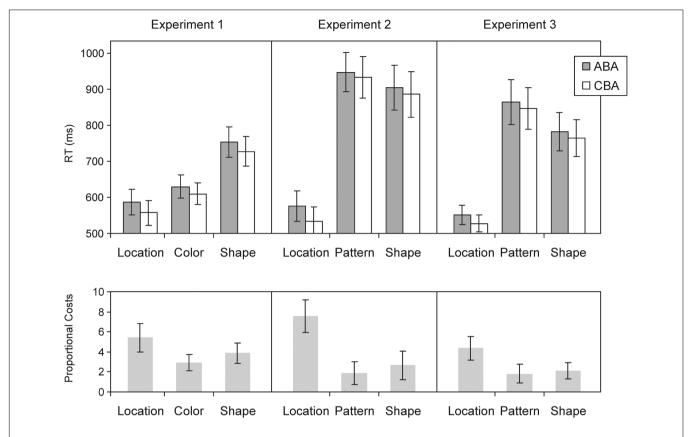
Stimuli and task were the same as in Experiment 1, except for the fact that the color task was replaced by a pattern task that we assumed to be more difficult. More precisely, the two objects were now filled with either horizontal or vertical lines (black/white). Both color and pattern tasks require attending the filling of an object (and are similar in this regard). The color task, however, might be easier because of the high distinctiveness of the used colors. The tasks were cued by the German words "Ort" (location) for the location task, "Muster" (pattern) for the pattern task, and "Form" (shape) for the shape task (note that the shape-task cue also differed from the one used in Experiment 1).

#### **Results and Discussion**

#### Task Dominance

Data trimming and analyses were performed as before. As suggested by **Figure 2**, the pattern task here was much more difficult than the color task in Experiment 1 (p < 0.0001 for the task comparison of the two experiments). Thus, exchanging the

Backward Inhibition and Task Dominance



**FIGURE 2 | (Top)** Response times (RTs) in Experiments 1–3 as a function of task and sequence. **(Bottom)** Proportional scores of the n–2 repetition costs (proportional RT differences between ABA and CBA sequences) calculated to account for basic RT differences across the tasks. Error bars indicate one standard error of the mean. In all three experiments, RTs are smaller in the location than in the other tasks reflecting the "dominance" of the location task. In addition, robust n–2 repetition costs are also evident in all three experiments, that is, RTs are longer when the task from trial n–2 was repeated (ABA sequence) than when the task switched. Importantly, this effect was larger for the location than for the other tasks. This especially holds when the n–2 repetition costs are set in relation to the absolute RTs in each task (see the proportional scores in the lower row of the figure).

tasks was effective. Again, performing the location task was the fastest. The ANOVA on RTs revealed a significant main effect of task, F(2,38) = 78.80, MSE = 22,594, p < 0.0001,  $GG-\varepsilon = 0.716$ . RTs in the location task were with on average 555 ms significantly shorter than in the pattern task (941 ms) and in the shape task (895 ms), ps < 0.01. Moreover, this location dominance was present in each single participant with an advantage in mean RTs of at least 90 ms.

Participants also committed fewer errors in the location task (1.24%) than in the pattern and shape tasks (5.43 and 4.07%). Both the main effect task, F(2,38) = 17.83, MSE = 10.25, p < 0.0001,  $GG-\varepsilon = 0.708$ , and the direct comparisons (ps < 0.0001) were significant.

All in all, combining the location and shape tasks with the new pattern task yielded a much more pronounced dominance pattern than in Experiment 1. Exchanging the color task by the pattern task, apparently also had an effect on the shape task. The direct comparisons of the two experiments yielded significantly larger shape-task RTs in Experiment 2 than in Experiment 1, F(1,38)=4.23, MSE=112,809, p=0.0466. The different cues used for indicating the shape task (the German words "Typ" versus "Form") might be the reason for the RT differences.

However, it is more plausible that feature (i.e., edge) detection for discriminating the different shapes is much easier when the objects are colored than when they are shaded. Regardless of the specifics, however, the findings from Experiment 2 suggest that the location task is clearly the dominant one when performed in the context of pattern and shape tasks.

#### **Backward Inhibition**

As in the first experiment, ABA and CBA sequences differed significantly in RTs, F(1,19)=12.70, MSE=1,399, p=0.0021, for the main effect of sequence. ABA sequences were processed more slowly in all tasks and the respective difference was with 40 ms larger in the location task than in the other two tasks (14 and 18 ms for the pattern and shape task, respectively). Although the interaction Task × Sequence did not reach significance when using the raw RTs, F(2,38)=1.72, MSE=1,303, p=0.2028,  $GG-\varepsilon=0.683$ , the ANOVA on the proportional scores (taking the RT differences across tasks into account), yielded significant differences, F(2,38)=5.33, MSE=36, p=0.013,  $GG-\varepsilon=0.852$ . N-2 repetition costs in the location task differed significantly from the costs in the pattern task (p<0.001) and in the shape task (p=0.038).

In error rates, neither the main effect of sequence, F(1,19) = 3.49, MSE = 1.39, p = 0.0772, nor the interaction Task × Sequence F(2,38) = 2.96, MSE = 3.10, p = 0.0850,  $GG-\varepsilon = 0.697$ , were significant. Descriptively, n-2 repetition costs were observed only for the pattern task (with 6.16% for ABA and 4.69% for CBA sequences).

To sum up, n-2 repetition costs in RTs were larger for the dominant location task. This pattern is in accordance with our hypothesis and suggests that the location task receives more inhibition, presumably to avoid interference on the weaker tasks. As argued in the Introduction, S-R compatibility was assumed to be a relevant factor behind task dominance. The location task, as it was implemented in the two experiments so far, was characterized by compatibility both on the element level as well as on the set level: the relevant dimensions of stimuli and responses (spatial location) did overlap and, in addition, the specific mapping between a stimulus and a response was compatible (i.e., left stimulus to a left response), which might have activated spatially corresponding responses in a more or less automatic fashion. To examine whether our task dominance effect on n-2 repetition costs is driven by the more general dimensional overlap with spatial stimulus and response set or by the existence of automatic response activation with spatially corresponding S-R mappings, we used spatially incompatible S-R mappings for the location task in Experiment 3.

#### **EXPERIMENT 3**

#### **Materials and Methods**

#### **Participants**

Twenty new students (15 female, 5 male) participated. None of them took part in the previous experiments. Mean age was 23.2 years (age range 18–31 years).

#### Stimuli, Task, and Procedure

Stimuli and tasks were the same as in Experiment 2. The only change was that in this experiment the S-R mapping for the location task was incompatible, that is, participants responded in the location task with a button press on the right when the stimulus was presented left and vice versa. The four possible mappings were counterbalanced across participants. Everything else was as before.

#### **Results and Discussion**

#### Task Dominance

As obvious from the figure, the location task was with a mean RT of 540 ms again processed much faster than the other two tasks with 856 and 773 ms. The main effect of task, F(2,38) = 45.75, MSE = 23,542, p < 0.0001,  $GG-\varepsilon = 0.627$ , and the comparisons of the location task with the other tasks (ps < 0.0001) were significant. For the error rates, significant differences across the tasks were obtained, too, F(2,38) = 9.72, MSE = 8.68, p = 0.0007,  $GG-\varepsilon = 0.880$ . Error rates were significantly lower in the location task (2.63%) than in the pattern task (5.42%) and the shape task (4.73%), with  $ps \le 0.001$ .

These findings indicate that despite the spatially incompatible S-R mapping used in Experiment 3, the location task is still easier than the other two tasks. This suggests that the relevant factor behind the location task's dominance is not compatibility on the element level, but rather compatibility on the set level (dimensional overlap). This finding is reminiscent of findings in the S-R compatibility literature, showing that the benefit of spatially compatible S-R mappings is basically lost in the context of mixed S-R mappings (i.e., when compatible and incompatible mappings are mixed, or when a location-relevant task is mixed with a location-irrelevant task, e.g., Proctor and Vu, 2006, for a review). In the present context, the data of Experiment 3 suggest that the potential benefit of spatial S-R correspondence was not fully shown in Experiments 1 and 2 because the mixed mappings might have suppressed this particular benefit. Presumably, had we included single-task control conditions, we might have found that the performance benefit in these blocks relative to the task-switching blocks would have been largest for the location task with the compatible mapping. However, in the absence of such single-task control conditions, we can only speculate that automatic response activation may not be the driving factor in the performance benefit of the location task relative to the other two tasks. That is, dimensional overlap more generally seems to matter.

In fact, in Experiment 3, RTs in the location task were not longer than in Experiment 2, in which the S–R mapping was compatible. RTs were even slightly shorter in Experiment 3 than in Experiment 2. If anything, then the RTs in the other two tasks increased in Experiment 3 compared to Experiment 2. However, these differences did not reach significance, F(2,76) = 2.54, MSE = 23,068, p = 0.107,  $GG-\varepsilon = 0.671$ , for the interaction Experiment × Task.

#### **Backward Inhibition**

As before, sequence had a significant effect, F(1,19)=17.93, MSE=677, p=0.0004. With 24 ms, which is an increase of 4.65%, the n-2 repetition costs were again slightly larger for the location than for the other two tasks. However, the interaction Task × Sequence was not significant (F<1). Also, with the proportional scores the differences did not reach significance, F(2,38)=2.20, MSE=18, p=0.1259,  $GG-\varepsilon=0.981$ .

In the error rates, small n-2 repetition costs were numerically present in all three tasks (with differences between ABA and CBA sequences of 0.28, 0.20, and 0.46% for the location, pattern, and shape tasks, respectively), which, however, did not reach significance, F(1,19) = 1.21, MSE = 2.43, p = 0.2847.

## COMMON ANALYSIS OF EXPERIMENTS 1–3

Across all three experiments, the n-2 repetition costs were numerically larger for the location task, thus, supporting our hypothesis that dominant tasks are inhibited more strongly. However, except for Experiment 2, these differences were not significant. Given that the n-2 repetition costs here are relatively small (23 ms on average, compared to, e.g., 80 ms in Schuch

and Koch, 2003, who used a different set of tasks), differences in these costs probably require a larger sample to be detected, that is, the failure of finding significant differences might be an issue of statistical power. We, therefore, ran analyses with a sample that includes all three experiments.

For the combined ANOVA (with experiment as factor), we directly tested the n-2 repetition costs in the location task against the average costs in the other two tasks. Both the test with the proportional costs as well as the test with the raw difference scores were significant, F(1,57)=14.61, MSE=23, p=0.0003 and F(1,57)=5.80, MSE=424, p=0.0193, respectively (no significant interactions with experiment, ps>0.22). Thus, increasing the power by pooling the data across the three experiments (with 20 participants each) revealed significant differences in the size of the n-2 repetition costs.

#### **GENERAL DISCUSSION**

Flexible switching between tasks is assumed to be accompanied by inhibiting strong competitor tasks or tasks that were relevant previously. This inhibitory process is thought to reduce conflict allowing one to efficiently perform the currently relevant task (Mayr and Keele, 2000; Koch et al., 2010). Given this, it is plausible to assume that stronger or more dominant tasks require more inhibition than weaker and less dominant ones. Evidence regarding this postulated relation between the dominance pattern of the tasks and the mechanisms applied to control intertask interference is scarce, because in research on task switching it is common practice to aggregate across tasks. Therefore, we here systematically manipulated task dominance and assessed n-2 repetition costs as an empirical marker of inhibition separately for each task.

Across three experiments, participants performed a location discrimination task with strong S–R bindings (i.e., dimensional overlap between stimuli and responses, see Kornblum et al., 1990) substantially faster and more accurately than color/pattern discrimination and shape discrimination tasks, for which S–R mappings were arbitrary. Because stimuli were multidimensional, conflict in processing the color/pattern and shape tasks arises because of an irrelevant S–R overlap with the response mappings of the location task (i.e., the irrelevant stimulus dimension spatial location [left vs. right presented objects] overlaps with the relevant response dimension [left vs. right manual response]). Consequently, the location task was not only processed faster and more accurately, but also can be assumed to be dominant in the context of the other tasks, because of the interference it exerts (similar to the Simon effect, Simon, 1990).

Along with the clear dominance pattern in overall performance, n-2 repetition costs differed across the tasks, showing larger costs for the dominant location task than for the two weaker tasks. This finding suggests that the amount of inhibition is adjusted to a task's dominance and, thus, extends our knowledge of inhibitory processes and their role for cognitive flexibility. Dominant tasks (or stimulus dimensions) such as the one used in our study, normally show strong interference on weaker tasks (cf. Simon effect, Simon, 1990; Lu and Proctor,

1995; see also Stroop effect, MacLeod, 1991, for review). In a task-switching situation, in which the dominant task/stimulus dimension was relevant recently, the potential source of task-set carry-over and interference seems to be counteracted by a relatively large degree of inhibition (see also Gade and Koch, 2005). In contrast, weaker and, thus, less interfering tasks seem to receive a smaller amount of inhibition. Although the observed differences in the size of the n-2 repetition costs were small and did not reach significance in each experiment, the basic pattern was observed in three experiments and thus proved replicable. Our data, thus, not only fit with previous evidence for an adjustment of the amount of inhibition to task difficulty (Arbuthnott, 2008), but extends this by providing evidence for a direct link between the dominance of a task and the amount of inhibition it receives to counteract the conflict it exerts.

The fact that the asymmetry in n-2 repetition costs are observed for different stimulus materials and tasks (see, e.g., Philipp et al., 2007; Declerck et al., 2015, for language switching; Arbuthnott, 2008, for task switching), in the first instance, provides strong evidence for the robustness and generality of this effect. Beyond that, it may also help to broaden our knowledge about the nature of inhibitory processes in task switching.

Specifically, as between-task interference in the various tasks typically used in task-switching studies arise in different ways, inhibition presumably also targets different aspects of processing, that is, the locus and focus of inhibition may differ across tasks and paradigms. For instance, Arbuthnott (2008) used digitcategorization tasks for which semantic aspects of a digit, such as magnitude or parity, are to be retrieved from long-term memory. In the present study, the stimuli for the color/pattern and shape tasks are multidimensional stimuli that contain an S-R overlap with the irrelevant stimulus dimension (left vs. right spatial location) overlapping with the relevant response dimension (left vs. right manual response). Accordingly, inhibition may be targeted at the irrelevant perceptual stimulus dimension location and its corresponding response. Conflict in the Simon task is assumed to result from an automatic response activation through a direct route that assesses long-term S-R associations (see, e.g., Hommel and Prinz, 1997; Proctor and Vu, 2006, for reviews). In this regard, inhibiting the location task in the present study might contain the suppression of this direct route.

One finding from our study seems to be particularly suggestive with regard to the suppression of the direct route. Comparing the results of Experiments 2 and 3 revealed that an incompatible mapping of stimuli and responses in the location task neither changed the dominance pattern nor the asymmetry of the n-2repetition costs. As already discussed above, this reminds one of the often observed elimination of the S-R compatibility effect under mixed-task conditions (Proctor and Vu, 2006, for review). The most widely accepted account for this is that the direct response-selection route is suppressed when S-R mappings are mixed (e.g., Proctor and Vu, 2002). In the present study, the absence of a strong S-R compatibility effect in the location task may indicate that in this specific task-switching context we have used here, the translation of the relevant stimulus code into a response code via the direct route is suppressed (even when the mapping was compatible). Although this needs to be addressed

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in further studies (e.g., by including pure blocks and a withinsubject manipulation of S–R compatibility), it provides a first hint that exactly this link to long-term representations is the locus of the inhibitory process when it comes to control potential conflict that arises from the location task.

The observed differences in the n-2 repetition costs as a function of task dominance were comparatively small and might, therefore, be of little importance in the microstructure of task switching. However, the n-2 repetition costs proper already proved to be rather small in the present study. Hence, it is not surprising that any difference in the size of the costs also turn out to be small. On the other hand, task dominance constitutes only one instance of a broader category of factors that determine the amount of inhibition needed to counteract conflict. As previous studies pointed out, factors such as the time elapsed between the tasks (e.g., Gade and Koch, 2005), the representational overlap of the response sets (Gade and Koch, 2007) as well as increased intertrial conflict (Grange and Houghton, 2010) are responsible for the magnitude of inhibition. Together these findings indicate that backward inhibition is a particularly flexible mechanism that is sensitive to many aspects of the context.

#### CONCLUSION

The present study provides evidence that in task-switching situations a dominant task receives more inhibition than weaker ones presumably to counteract the potential source of task-set carry-over to subsequent trials. This finding fits with previous

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demonstrations that the degree of inhibition can vary with particular context demands. Extending these findings, the effects in the present study suggest a direct link between a task's activation and the inhibition it receives. Inhibition as a means of cognitive flexibility, thus, is not a "blunt" mechanism enabled whenever interference is likely to occur, but adjusted in strength according to specific requirements of the context and the dominance dynamic of the tasks.

#### **AUTHOR CONTRIBUTIONS**

KJ, IK, and VH designed the study. KJ (assisted by VH) analyzed the data. KJ, IK, and VH discussed the results. KJ wrote the first draft of the manuscript. IK and VH commented on the draft. All authors approved the final manuscript. All authors agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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# Task Inhibition and Response Inhibition in Older vs. Younger Adults: A Diffusion Model Analysis

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Differences in inhibitory ability between older (64–79 years, N=24) and younger adults (18–26 years, N=24) were investigated using a diffusion model analysis. Participants performed a task-switching paradigm that allows assessing n-2 task repetition costs, reflecting inhibitory control on the level of tasks, as well as n-1 response-repetition costs, reflecting inhibitory control on the level of responses. N-2 task repetition costs were of similar size in both age groups. Diffusion model analysis revealed that for both younger and older adults, drift rate parameters were smaller in the inhibition condition relative to the control condition, consistent with the idea that persisting task inhibition slows down response selection. Moreover, there was preliminary evidence for task inhibition effects in threshold separation and non-decision time in the older, but not the younger adults, suggesting that older adults might apply different strategies when dealing with persisting task inhibition. N-1 response-repetition costs in mean RT were larger in older than younger adults, but in mean error rates tended to be larger in younger than older adults. Diffusion-model analysis revealed longer non-decision times in response repetitions than response switches in both age groups, consistent with the idea that motor processes take longer in response repetitions than response switches due to persisting response inhibition of a previously executed response. The data also revealed age-related differences in overall performance: Older adults responded more slowly and more accurately than young adults, which was reflected by a higher threshold separation parameter in diffusion model analysis. Moreover, older adults showed larger non-decision times and higher variability in non-decision time than young adults, possibly reflecting slower and more variable motor processes. In contrast, overall drift rate did not differ between older and younger adults. Taken together, diffusion model analysis revealed differences in overall performance between the age groups, as well as preliminary evidence for age differences in dealing with task inhibition, but no evidence for an inhibitory deficit in older age.

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#### INTRODUCTION

According to the prominent "inhibition deficit hypothesis," inhibitory functions deteriorate in older age (e.g., Hasher et al., 1999, 2007). To date, the evidence for an inhibition deficit in older age is mixed; it seems that different forms of inhibition need to be distinguished (e.g., Andrés et al., 2008; Germain and Colette, 2008; Borella et al., 2009; Anguera and Gazzaley, 2012).

Different paradigms have been developed in cognitive psychology to investigate inhibitory functions, many of which assess "low-level" inhibitory functions such as inhibition of previously attended stimulus locations (e.g., Taylor and Klein, 1998; Wang and Klein, 2009), inhibition of previously ignored stimuli (e.g., Fox, 1995; May et al., 1995; Tipper, 2001), or the stopping of ongoing responses (e.g., Verbruggen and Logan, 2008). The present study focuses on "higher-level" inhibitory functions that are involved in task switching performance, facilitating flexible switching between different tasks. Specifically, task inhibition and response inhibition in task switching are being investigated, assessing potential age-related differences in these inhibitory functions.

To investigate the ability to inhibit a previous task that is no longer relevant, a task-switching paradigm has been developed measuring "n-2 task repetition costs" (Mayr and Keele, 2000; for reviews, see Koch et al., 2010; Gade et al., 2014). The basic idea is that switching from task A to task B involves inhibition of the no longer relevant task A. When switching back to A after just one intermediate trial (ABA task sequence), task A is still inhibited and this persisting inhibition needs to be overcome, leading to performance costs, relative to task sequences where at least two intermediate trials have occurred before switching back to task A, and hence there is less persisting inhibition of A (CBA task sequence).

Another inhibitory function involved in task-switching performance is response inhibition, serving to prevent perseveration of a response that has already been executed (e.g., Rogers and Monsell, 1995; Houghton and Tipper, 1996; Druey and Hübner, 2008). Response inhibition can be measured by assessing response-repetition costs in task-switching paradigms (e.g., Hübner and Druey, 2006; Koch et al., 2011; Druey, 2014). Repeating the response from the previous trial takes longer than switching the response, due to persisting response inhibition. This response-repetition cost only becomes apparent in task-switch trials, when the same response needs to be repeated in a different task context. In task repetitions, the response-repetition cost is overcompensated by other cognitive processes, such as category priming or episodic binding (cf. Oberauer et al., 2013; Druey, 2014).

On the basis of the inhibition-deficit-theory of aging (see also Dempster, 1992; Hasher et al., 1999, 2007; Gazzaley, 2012), one would expect task inhibition and response inhibition to be diminished in older as compared to younger adults. So far, however, empirical support for such age-related diminution of task inhibition and response inhibition has not been reported. Mayr (2001) compared n−2 task repetition costs and responserepetition effects in young vs. older adults. If anything, older adults showed even larger n-2 task repetition costs than younger adults. With respect to response-repetition effects, Mayr (2001) found age differences in task repetitions, with larger responserepetition benefit in older than younger adults. Responserepetition costs in task switches were small and were not compared directly between the age groups, because response inhibition was not in the focus of interest in that study. Lawo et al. (2012) also looked at n-2 task repetition costs in older vs. younger adults, and found n−2 task repetition costs of similar size in both age groups (see also Li and Dupuis, 2008). In both Mayr's (2001) and Lawo et al.'s (2012) study, the inhibition effects were observed in mean RT data; inhibition effects in mean error rates were small and non-significant. Pettigrew and Martin (2015) observed increased n-2 task repetition costs in older as compared to younger adults when computing "rate residual scores," which are a composite measure of RT and error rates that controls for potential age differences in processing speed (cf. Hughes et al., 2014). Response-repetition costs were not analyzed in this latter study. Hence, if anything, task inhibition has been found to be larger in older than younger adults, and response inhibition has not been systematically compared between older vs. younger adults.

In the above-mentioned studies, the data were analyzed by computing mean performance per experimental condition (e.g., mean RT in ABA vs. CBA trials), or by comparing the residuals of a regression of the more difficult ABA condition on the easier CBA condition (Pettigrew and Martin, 2015). It is possible that subtle differences in the shape of RT distributions of older vs. younger adults are not detected by such approaches. A more exhaustive analysis of choice-RT data can be obtained by applying the diffusion model (Ratcliff, 1978; Ratcliff and McKoon, 2008; Ratcliff et al., 2015, 2016), taking into account the response time distributions of both correct and error responses. The model parameters can be interpreted in terms of cognitive processes, making it possible to draw inferences about the cognitive mechanisms underlying age differences in behavioral performance (cf. Matzke and Wagenmakers, 2009; Voss et al., 2013, 2015).

The diffusion model assumes that evidence for one or the other response alternative is accumulated until a threshold is reached, after which this response is executed (see Figure 1 for an illustration). In its simplest version, the model has three parameters: The speed of evidence accumulation is described by the drift rate parameter; the amount of evidence required before a response is selected is described by the threshold separation parameter; these two parameters determine the shape of the response time distribution. A third parameter subsumes all processes before and after the response selection process and is therefore called non-decision time parameter. Apart from these three basic parameters, the starting point can be varied as well, modeling biases toward one or the other response alternative. Moreover, variability in starting point, drift rate, and non-decision time can be introduced as additional parameters. Variability in starting point and drift rate have only small impact on the shape of the resulting response time distribution (cf. Voss et al., 2013); a recent study by Lerche and Voss (2016) showed that using a more parsimonious model with these variability parameters fixed to zero can be superior to more complex models. Variability in non-decision time has a larger impact on the shape of the distribution; therefore, it has been recommended to include non-decision time variability in the model in order to achieve stable parameter estimates (Voss et al., 2015; Lerche and Voss, 2016).

The diffusion model has been applied extensively to assess the effects of aging on performance in choice-RT tasks (e.g., Thapar

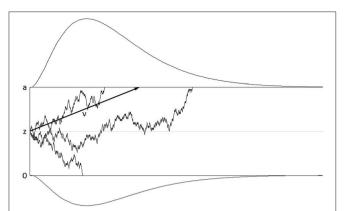


FIGURE 1 | Illustration of the basic diffusion model. Time passes from left to right. The upper and lower thresholds represent the amount of evidence necessary to select one or the other response alternative, respectively. The upper threshold corresponds to the correct response alternative, the lower threshold to the wrong response alternative. Evidence accumulation starts at starting point z and continues until one of the thresholds is reached. Evidence accumulation is influenced by random noise; the average rate of evidence accumulation (drift rate v) is shown by the black arrow. The drifts of three individual trials are shown. Reaction time is a linear function of the duration of the drift process; reaction time distributions for the correct and wrong response alternative are illustrated above and below the thresholds.

et al., 2003; Ratcliff et al., 2006a,b, 2007, 2011; Spaniol et al., 2006; McKoon and Ratcliff, 2013; Ratcliff and McKoon, 2015). It is usually found that older adults respond more slowly, but also more accurately, than younger adults, which is reflected in a larger threshold separation parameter in older than younger adults in diffusion model analysis. Moreover, motor processes have been found to be prolonged in older age, leading to increased non-decision time parameters in older compared to younger adults. In contrast, the quality of information on which the decision is based is often as good in older as in younger adults, as reflected in comparable drift rates across age groups.

Regarding n-2 task repetition costs in young adults, a previous study from our lab has found the ABA-CBA difference to be reflected in the drift rate, with smaller drift rate in ABA than CBA trials (Schuch and Konrad, under review). This finding is in line with previous diffusion-model studies of task-switching performance, where carry-over effects of previous task sets have been found to be reflected in drift rate (Schmitz and Voss, 2012, 2014). Because n-2 task repetition costs are thought to be a measure of persisting inhibition of a previously abandoned task set, they, too, constitute a carry-over effect of previous task sets. Interestingly, Schuch and Konrad (under review) showed that n-2 task repetition costs in a group of 9-11 year old children were not reflected in drift rate, but in non-decision time, suggesting that different cognitive processes might be underlying n−2 task repetition costs in children vs. young adults. In light of these findings the question arises as to whether n-2 task repetition costs in older vs. younger adults might result from partly different cognitive processes as well, as could be revealed by diffusion model analysis. Regarding response-repetition costs in task switching, these have not been systematically investigated using diffusion model analysis. It is conceivable that response inhibition is reflected in non-decision time, slowing motor processes in response-repetition relative to response-switch trials.

In the present study, task inhibition and response inhibition were assessed in a group of older and younger adults. First, mean RTs and error rates were analyzed. Because RTs were expected to be considerably slower in older than younger adults, log-transformed RTs were analyzed in addition to raw RTs. By computing the inhibition effects on the basis of mean log RTs, age-related differences in overall cognitive speed can be accounted for (e.g., Kray and Lindenberger, 2000; Salthouse and Hedden, 2002; as a side effect, the log transformation also reduces skewness of the RT distribution, e.g., Ratcliff, 1993). Second, a diffusion model analysis was performed on the raw data in order to investigate which cognitive processes underlie the inhibition effects in the two age groups. Based on previous studies, it was predicted that task inhibition is reflected in the drift rate parameter, at least in young adults. Response inhibition was predicted to be reflected in the non-decision time parameter, reflecting prolonged motor processes. Comparing diffusion model parameters of young vs. old adults will allow investigating potential age differences in task inhibition and response inhibition.

#### **METHODS**

## **Participants**

Twenty-four older adults (range 64–79 years; mean age 71.7 years, *SD* 4.0; 12 female; 12 male) were recruited from the voluntary participants list of the Cognitive and Experimental Unit at Institute of Psychology, RWTH Aachen University, and received 8 Euros for participation. All older adults were retired; the period of retirement varied from 1 to 17 years (mean 9.3 years, *SD* 4.6). The DemTect (Kessler et al., 2000) was administered to control for potential signs of dementia; the participants' DemTect values varied between 15 and 18 (mean 17.4; *SD* 0.8), and hence were all within the normal range. (The maximum DemTect value is 18; values above 13 are considered normal in people of 60 years or older).

Twenty-four young adults (range 18–26 years; mean age 21.0 years, *SD* 2.6; 12 female; 12 male) were recruited from the Aachen area; they were either students, or friends of students, of RWTH Aachen University, and received 8 Euros or partial course credits for participation. One participant in the young adult group was replaced because of showing a two-peaked RT distribution. (The overall RT distribution, as well as the separate distributions of ABA and CBA, and of response repetitions and response switches, all showed two peaks in this participant, possibly indicating that this person applied two different strategies when performing the experiment. The RT distributions of all other participants and conditions were all one-peaked).

The study was in accordance with the Declaration of Helsinki. All participants gave written informed consent to participate in the study.

## Stimuli, Tasks, and Responses

The stimuli were standardized facial photographs of 20 young adults (20–30 years old) and 20 older adults (60–70 years old).

Each portrait was presented inside a colored frame, with frame color indicating which task to perform. A blue frame indicated to categorize the person as male or female; a red frame to categorize the person as young or old; a yellow frame to categorize the emotional expression as happy or angry. The 40 faces consisted of 5 young male happy faces, 5 young male angry, 5 young female happy, 5 young female angry, 5 old male happy, 5 old male angry, 5 old female happy, 5 old female angry. The color frames (14.5 cm in height and 11 cm in width; frame line of 0.3 cm thickness) were presented centrally on a black computer screen. The portraits (14.1 cm in height size, 10.6 cm in width) were presented centrally inside the frames. The computer screen was situated about 50 cm in front of the participants. Participants responded by pressing one of two response keys on a German computer keyboard (the "x" and "," keys, which are located just above the left and right end of the space bar, respectively) with their left or right index finger, respectively. Half of the participants in each age group responded to happy, young, and male, faces by pressing the left key, and to angry, old, and female faces by pressing the right key. To the other half of the participants, the reversed mapping was assigned (right for happy, young, male; left for angry, old, female). The paradigm was the same as in the study by Schuch and Konrad (under review; see Schuch et al., 2012, for further details of the stimulus material).

#### **Procedure**

Participants were instructed orally by the experimenter; in addition, written instructions were presented on the screen. Participants were encouraged to respond as quickly and as accurately as possible. The experimenter stayed in the room over the whole period of the experiment. Participants completed four practice blocks of 60 trials each. In practice blocks 1–3, the tasks were practiced separately (gender categorization task in block 1, age categorization task in block 2, emotion categorization task in block 3). In practice block 4, all three tasks occurred in pseudo-random order.

The experimental phase consisted of four blocks of 60 trials each, which were separated by short breaks. Cues and stimuli occurred in pseudo-random order, with the following constraints. (1) Immediate task repetitions were not allowed. (2) Each task occurred equally often in each block. (3) There were roughly equal numbers of n-2 task repetitions and n-2 task switches per block. (4) Each of the 40 stimuli occurred six times during the experimental blocks, and six times during the practice phase. (5) Each stimulus was presented twice in the context of each task during the experimental blocks, and twice in the context of each task during the practice blocks. (6) The person presented in a particular trial n was never the same as the persons presented in trials n-1 and n-2. (7) There were roughly equal numbers of response repetitions and response switches from trial n-2 to n-1within each block and within the ABA and CBA task sequences.

Every trial started with the presentation of a red, blue, or yellow frame for 500 ms, followed by the presentation of a photograph inside the frame. Frame and picture stayed on the screen until the left or right response key was pressed. Then the screen turned black for 1000 ms. If the wrong key was pressed, an error feedback occurred after 500 ms of blank screen and lasted for 1000 ms, after which the screen turned black again for another 500 ms.

## Design

For the analysis of task inhibition, a  $2 \times 2$  design was applied with the independent variables Task Sequence (ABA vs. CBA) and Age Group (older vs. young adults). For the analysis of response inhibition, a 2 × 2 design was applied with the independent variables Response Transition (response repetition vs. response switch from trial n−1 to n) and Age Group (older vs. young adults). The two kinds of inhibition were analyzed separately in order to have a sufficient number of trials per condition for robust parameter estimation in the diffusion model analysis. For analysis of mean performance per experimental condition, the dependent variables were RTs, log RTs, and error rates. For diffusion model analysis, dependent variables were the parameters drift rate, threshold separation, non-decision time, and variability of nondecision time.

## **RESULTS**

## Data Filtering

The first two trials from each experimental block (which could not be classified as ABA or CBA) were removed from analysis, as well as the two trials following an error (to eliminate potential influences of error aftereffects). Outliers were removed as well; these were defined following the procedure recommended by Schmiedek and colleagues (Schmiedek et al., 2007; see also Steinhauser and Hübner, 2009; Moutsoupoulou and Waszak, 2012). That is, trials with RT faster than 200 ms were excluded, then trials with RT higher than four standard deviations above each participant's mean per experimental condition were defined as outliers. This process was repeated on the remaining trials until there were no further outliers. For analysis of mean RTs, error trials were excluded as well; for analysis of error rates and diffusion model analysis, error trials were included. For analysis of task inhibition, the mean number of trials per condition in young adults were 98.9 (SD 8.0; range 78–108) in ABA and 102.3 (SD 7.8; range 86-112) in CBA condition; in the older adults, there were 102.2 (SD 7.1; range 86-114) in ABA and 107.1 (SD 6.4; range 89-116) in CBA condition. For analysis of response inhibition, the mean number of trials per condition in young adults were 96.1 (SD 8.3; range 72-106) in response repetitions and 105.1 (SD 8.0; range 91-117) in response switches; in the older adults, there were 101.4 (SD 6.2; range 87-110) in response repetitions and 107.8 (SD 7.2; range 93–120) in response switches.

The analyses were performed on 24 young and 24 older adults. Because variability in the inhibition effects was large in diffusion model parameters, secondary analyses were conducted where participants with outlying inhibition effects in one or more of the model parameters were excluded (see Supplementary Figure 1). For the secondary analysis of task inhibition, this affected two young and six older adults; for response inhibition, this affected two young and two older adults. To foreshadow the results, the overall data pattern was similar in both types of analyses. Statistically, the pattern of main effects was the same in both

types of analyses, but the interactions of inhibition effects and age group were only significant on the 5% level in the analysis where participants with outlying inhibition effects were excluded. The interpretation of the data pattern is solely based on this secondary analysis.

## **Diffusion Model Analysis**

#### **Parameter Settings**

The software "fast-dm" (Voss and Voss, 2007; Voss et al., 2015) was used to estimate the four parameters drift rate ( $\nu$ ), threshold separation (a), non-decision time  $(t_0)$ , and variability of non-decision time  $(s_{t0})$ . The starting point bias was set to 0.5 a (i.e., in the middle between the two thresholds); this was done because the thresholds were associated with correct and erroneous responses (cf. Schmitz and Voss, 2012, 2014). All other parameters implemented in fast-dm were set to zero in order to keep the model as parsimonious as possible; this has been shown to improve estimation of the main parameters (Lerche and Voss, 2016; van Ravenzwaaij et al., 2016). The four parameters v, a,  $t_0$ , and  $s_{t0}$  were estimated separately for each individual and each condition (ABA vs. CBA in the task-inhibition analysis; response repetition vs. response switch in the response-inhibition analysis).

#### Model Fit

The Kolmogorov-Smirnow (KS) statistic provided by the fastdm software did not reveal any significant deviations between empirical and estimated RT distributions, ps > 0.21 for the analysis of task inhibition, ps > 0.30 for the analysis of response inhibition, suggesting that the model fitted the data reasonably well for all participants and all conditions. For visual inspection of model fit, the cumulative density functions (cdfs) were computed for each individual and each condition, and plotted together with the p-values of the KS statistic (see Supplementary Figures  $2, 3)^1$ .

<sup>1</sup>Note that the standard criterion of p < 0.05 for the KS statistic to indicate poor model fit might not be ideally suited for all experimental settings. When trial numbers are relatively small (such as in the present study, where there are about 100 observations per condition), the power to detect misfits is relatively small. In contrast, when trial numbers are very large, even small misfits will reveal a significant p value of the KS statistic. One way to overcome this problem would be to run simulations in order to define an appropriate criterion adapted to the specific experimental setting (Voss et al., 2013). In the present study, we checked

TABLE 1 | Analysis of task inhibition: Results of the 2 x 2 ANOVAs with within-subjects variable Task Sequence (ABA, CBA) and between-subjects variable Age Group (young adults, older adults).

Dependent measure	Main effect Age Group			Main effect Task Sequence			Interaction Task Sequence × Age Group		
	F <sub>(1, 46)</sub>	p	$\eta_p^2$	F <sub>(1, 46)</sub>	p	$\eta_p^2$	F <sub>(1, 46)</sub>	p	$\eta_p^2$
MEAN PERFORMANC	E								
RT	56.72	< 0.05	0.55	22.22	< 0.05	0.33	<1.0	n.s.	
Log RT	94.75	< 0.05	0.67	29.21	< 0.05	0.39	<1.2	n.s.	
Error Rates	4.14	< 0.05	0.08	8.42	< 0.05	0.16	<1.0	n.s.	
DIFFUSION MODEL PA	ARAMETERS								
а	7.38	< 0.05	0.14	6.05	< 0.05	0.12	2.42	=0.13	0.05
ν	<1.0	n.s.		9.11	< 0.05	0.17	2.68	=0.11	0.06
$t_0$	116.38	< 0.05	0.72	4.61	< 0.05	0.09	<1.0	n.s.	
s <sub>t0</sub>	25.15	< 0.05	0.35	<1.0	n.s.		<1.0	n.s.	

(B) Analysis including only participants with non-outlying task inhibition effects in model parameters (22 young adults, 18 older adults).

Dependent measure	Main effect Age Group			Main effect Task Sequence			Interaction Task Sequence × Age Group		
	F <sub>(1,38)</sub>	p	$\eta_{P}^{2}$	F <sub>(1, 38)</sub>	p	$\eta_p^2$	F <sub>(1,38)</sub>	р	$\eta_p^2$
MEAN PERFORMANC	E								
RT	75.49	< 0.05	0.67	18.10	< 0.05	0.32	<1.0	n.s.	
Log RT	102.33	< 0.05	0.73	21.75	< 0.05	0.36	<1.0	n.s.	
Error Rates	4.59	< 0.05	0.11	8.76	< 0.05	0.19	<1.0	n.s.	
DIFFUSION MODEL PA	ARAMETERS								
а	6.45	< 0.05	0.15	8.87	< 0.05	0.19	5.11	< 0.05	0.12
ν	<1.0	n.s.		16.21	< 0.05	0.30	3.78	=0.06	0.09
$t_0$	92.48	< 0.05	0.71	11.14	< 0.05	0.23	5.93	< 0.05	0.14
s <sub>t0</sub>	23.46	< 0.05	0.38	<1.0	n.s.		<1.0	n.s.	

## **Analysis of Task Inhibition**

Results of the  $2 \times 2$  ANOVAs with the independent variables Task Sequence (ABA vs. CBA) and Age Group (old vs. young adults) are described in Table 1. Specifically, Table 1A shows the ANOVAs including all participants; Table 1B shows the ANOVAs including only the participants with non-outlying task inhibition effects in model parameters. Figure 2 shows mean performance for ABA and CBA trials, as well as results from diffusion model analysis (all based on the analyses with non-outlying participants only). Figure 3 illustrates the RT distributions resulting from mean diffusion model parameters in ABA and CBA conditions in the two age groups. For illustrative purposes, the scale of error RT distributions is ten times larger than the scale of correct RT distributions.

whether excluding all participants with p values smaller than 40 in the KS statistic would change the data pattern; it did not. Therefore, it was assumed that the model fitted the data sufficiently well for all participants.

Overall, mean RT was larger, and error rate was smaller, in older than younger adults. In diffusion model analysis, this was reflected by larger non-decision time, variability of nondecision time, as well as larger threshold separation in the older as compared to the younger adults. In contrast, drift rate did not differ between the age groups.

Regarding task inhibition, there were n-2 task repetition costs across both age groups in mean RT, mean log RT, and mean error rates, which did not differ statistically between older and younger adults. Diffusion model analysis revealed that the task inhibition effect was reflected in drift rate, threshold separation, and non-decision time, across both age groups. In ABA trials, drift rate was smaller, threshold separation smaller, and non-decision time was larger, than in CBA trials. This data pattern tended to be more pronounced in the old than young adults; the interactions of task inhibition and age group were not significant on a 5% alpha level when all participants were included, but were significant (or marginally significant) when

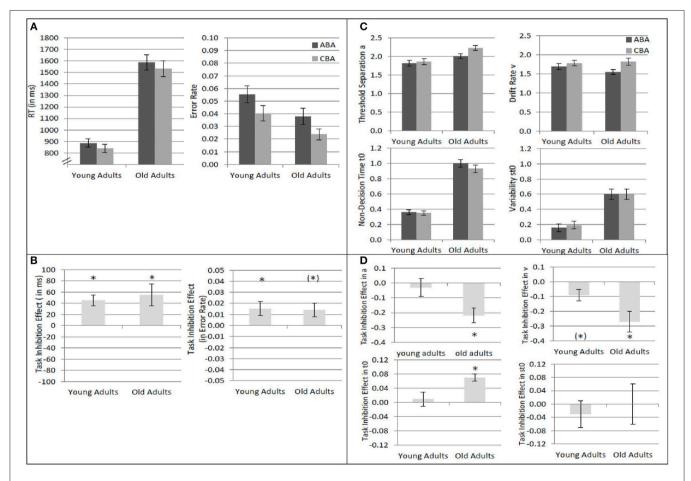


FIGURE 2 | Analysis of task inhibition (ABA vs. CBA task sequences) in young adults (18-26 years; N = 22) and older adults (64-79 years; N = 18). (A) Mean reaction times and mean error rates in ABA and CBA trials. (B) Mean task inhibition effect (ABA-CBA) in reaction times and error rates. (C) Diffusion model parameters threshold separation a, drift rate  $\nu$ , non-decision time  $t_0$ , and variability of non-decision time  $s_{t0}$ , separately for ABA and CBA trials, and young and older adults. Units on the y-axis represent the untransformed values as obtained by the fast-dm software (Voss and Voss, 2007; diffusion coefficient = 1.0). The units represent amount of evidence for a; evidence per time for ν; time (in s) for t<sub>0</sub> and s<sub>t0</sub>. (D) Mean task inhibition effect (ABA–CBA) in diffusion model parameters. Error bars indicate 1 standard error of mean. \* indicates significant task inhibition effect, i.e., p < 0.05 for the two-tailed t-test comparing ABA and CBA within each age group; (\*) indicates p < 0.10 for the two-tailed t-test.

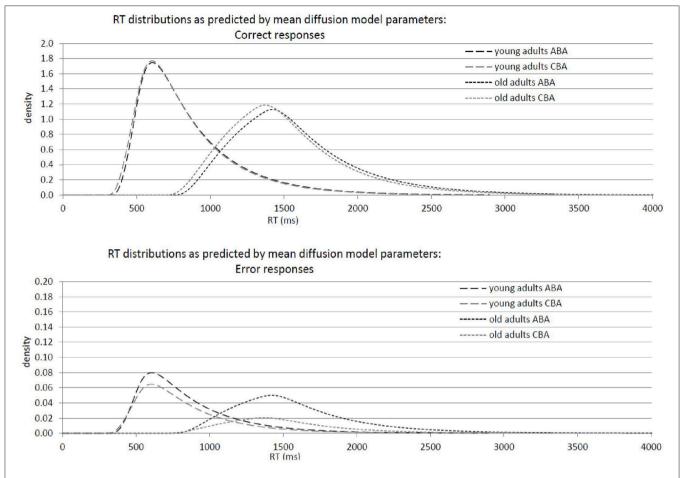


FIGURE 3 | Graphical illustration of response-time distributions resulting from mean diffusion model parameters in ABA and CBA conditions in young adults (18–26 years; N = 22) and older adults (64–79 years; N = 18). Upper panel: Distribution of correct responses. Lower panel: Distribution of error responses.

only participants with non-outlying inhibition effects were included. These interactions were analyzed further by analyzing the age groups separately with *post-hoc* two-tailed *t*-tests. In the older adults, the task inhibition effect was significant in drift rate,  $t_{(17)} = 3.26$ , p < 0.01, threshold separation,  $t_{(17)} = 3.94$ , p < 0.01, and non-decision time,  $t_{(17)} = 4.09$ , p < 0.01. In the young adults, the task inhibition effect was marginally significant in drift rate,  $t_{(21)} = 2.05$ , p = 0.05, and in none of the other parameters,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and in none of the other parameters,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and in none of the other parameters,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and in none of the other parameters,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and in none of the other parameters,  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and  $t_{(21)} = 1.05$ , and  $t_{(21)} = 1.05$ ,  $t_{(21)} = 1.05$ , and  $t_{(21)} = 1.05$ , and t

## **Analysis of Response Inhibition**

Results of the  $2 \times 2$  ANOVAs with the independent variables Response Transition (Response Repetition vs. Response Switch from n-1 to n) and Age Group (old vs. young adults) are described in **Table 2. Table 2A** shows the ANOVAs including all participants; **Table 2B** shows the ANOVAs including only the participants with non-outlying response inhibition effects in model parameters. **Figure 4** shows mean performance in response repetitions and switches, as well as results from diffusion model analysis (all based on the analyses with non-outlying participants only). **Figure 5** illustrates the RT distributions resulting from mean diffusion model parameters

per condition and age group. For illustrative purposes, the scale of error RT distributions is ten times larger than the scale of correct RT distributions.

The differences in overall performance obtained in the analysis of task inhibition were confirmed: Mean RT was larger, error rate smaller, the diffusion model parameters non-decision time, and variability of non-decision time were larger in older than younger adults; drift rate did not differ between the age groups. (Threshold separation was larger in older adults in the analysis including all participants, but this effect was not significant when the participants with outlying response inhibition effects were excluded).

There were n-1 response repetition costs across both age groups in mean RT and mean log RT, but not in error rates. Response-repetition costs in mean RT tended to be larger in older than younger adults, but in mean error rates, tended to be smaller in older than younger adults. Diffusion model analysis revealed that response-repetition costs were reflected in non-decision time across both age groups, with longer non-decision time in response repetitions than switches. (As can be seen from **Figure 4**, when the age groups were assessed separately, this effect

TABLE 2 | Analysis of Response Inhibition: Results of the 2 x 2 ANOVAs with within-subjects variable Response Transition (Response Repetition, Response Switch) and between-subjects variable Age Group (young adults, older adults).

(A) Analysis including all participants (24 young adults, 24 older adults).

Dependent measure	Main effect Age Group			Main effect Response Transition			Interaction Response Transition × Age Group		
	F <sub>(1, 46)</sub>	p	$\eta_p^2$	F <sub>(1, 46)</sub>	p	$\eta_p^2$	F <sub>(1, 46)</sub>	р	$\eta_p^2$
MEAN PERFORMANC	E								
RT	56.76	< 0.05	0.55	12.83	< 0.05	0.22	2.93	=0.09	0.06
Log RT	94.69	< 0.05	0.67	20.32	< 0.05	0.31	1.84	=0.18	0.04
Error Rates	4.40	< 0.05	0.09	<1.0	n.s.		4.54	< 0.05	0.09
DIFFUSION MODEL PA	ARAMETERS								
а	4.79	< 0.05	0.09	<1.6	n.s.		<1.0	n.s.	
ν	<1.7	n.s.		<1.0	n.s.		<1.0	n.s.	
$t_0$	133.07	< 0.05	0.74	7.91	< 0.05	0.15	<1.6	n.s.	
s <sub>t0</sub>	26.20	< 0.05	0.36	<1.2	n.s.		<1.0	n.s.	

(B) Analysis including only participants with non-outlying response inhibition effects in model parameters (22 young adults, 22 older adults).

Dependent measure	Main effect Age Group			Main effect Response Transition			Interaction Response Transition × Age Group		
	F <sub>(1,42)</sub>	p	$\eta_P^2$	F <sub>(1,42)</sub>	р	$\eta_p^2$	F <sub>(1,42)</sub>	р	$\eta_p^2$
MEAN PERFORMANC	E								
RT	65.07	< 0.05	0.61	17.68	< 0.05	0.30	4.48	< 0.05	0.10
Log RT	86.14	< 0.05	0.67	19.57	< 0.05	0.32	1.81	=0.19	0.04
Error Rates	3.49	=0.07	0.08	<1.0	n.s.		3.47	=0.07	0.08
DIFFUSION MODEL PA	ARAMETERS	;							
а	1.82	=0.19	0.04	<1.0	n.s.		<1.0	n.s.	
ν	<1.0	n.s.		<1.0	n.s.		<1.6	n.s.	
$t_0$	115.82	< 0.05	0.73	4.88	< 0.05	0.10	<1.2	n.s.	
s <sub>t0</sub>	21.97	< 0.05	0.34	<1.0	n.s.		<1.0	n.s.	

was only marginally significant in the older adults, and not in the young adults.) The interaction of response inhibition and age group was not significant in any of the parameters.

## Combined Analysis of Task Inhibition and Response Inhibition

In order to check for potential interactions between task inhibition and response inhibition, the data were also analyzed in a  $2 \times 2 \times 2$  ANOVA with the independent variables Task Sequence and Response Transition, as well as the between-subjects variable Age Group. The results are presented in **Table 3**; there were no significant interactions, neither of task inhibition and response inhibition, nor of task inhibition, response inhibition, and age group.

#### DISCUSSION

The present study set out to investigate potential differences in inhibitory ability between younger and older adults. Two kinds of higher-level inhibition were investigated: task inhibition and response inhibition. Both effects were measured in a taskswitching paradigm, where participants switched between three different face categorization tasks and every trial constituted a task switch. Task inhibition was measured as the difference between task sequences of type ABA (n-2 task repetition) vs. CBA (n-2 task switch); response inhibition was measured as the difference between response repetitions vs. response switches from trials n-1 to n. In addition to analysis of mean performance, diffusion modeling was applied, providing a more fine-grained picture of potential age differences in task inhibition and response inhibition. The results showed differences in overall performance between the age groups, but no evidence for reduced inhibitory ability in older adults, neither in mean performance nor in diffusion model parameters. These findings are discussed in more detail below.

## **Overall Performance**

Regarding overall performance, older adults showed larger mean RTs, and smaller error rates, than younger adults, a finding that has long been known in the literature on aging (e.g., Rabitt, 1979; Salthouse, 1979; Smith and Brewer, 1995). In diffusion model analysis, this was reflected by a trend for larger threshold separation in older than younger adults (significant in the task-inhibition analysis, but not in the response-inhibition analysis).

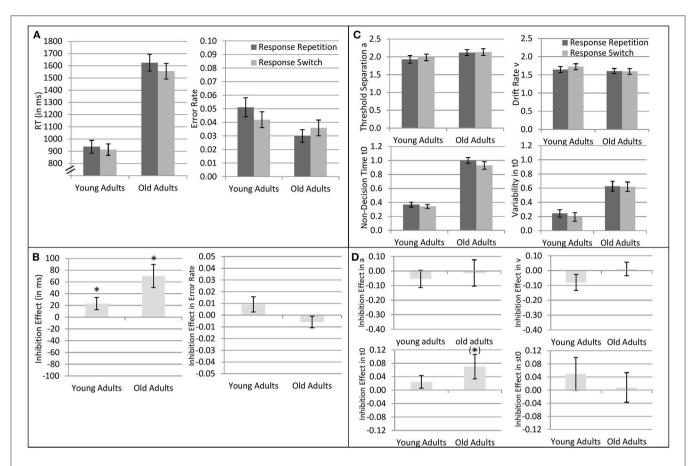


FIGURE 4 | Analysis of response inhibition (response repetitions vs. response switches from trial n-1 to n) in young adults (18–26 years; N=22) and older adults (64-79 years; N = 22). (A) Mean reaction times and mean error rates in response repetitions and switches. (B) Mean response inhibition effect (repetition-switch) in reaction times and error rates. (C) Diffusion model parameters threshold separation a, drift rate  $\nu$ , non-decision time  $t_0$ , and variability of non-decision time  $s_{t0}$ , separately for response repetitions and switches, and young and older adults. Units on the y-axis represent the untransformed values as obtained by the fast-dm software (Voss and Voss, 2007; diffusion coefficient = 1.0). The units represent amount of evidence for a; evidence per time for v; time (in s) for  $t_0$  and  $s_{t0}$ . (D) Mean response inhibition effect (repetition-switch) in diffusion model parameters. Error bars indicate 1 standard error of mean. \* indicates significant response inhibition effect, i.e., p < 0.05 for the two-tailed t-test comparing response repetition and response switch within each age group; (\*) indicates p < 0.10 for the two-tailed t-test.

The threshold separation parameter can be interpreted as a marker of speed-accuracy trade off, and previous research has shown repeatedly that older adults emphasize accuracy over speed more than do younger adults (Ratcliff et al., 2007, 2010, 2011; Starns and Ratcliff, 2010, 2012; Ratcliff and McKoon, 2015). Moreover, non-decision time and variability of nondecision time were larger in older than younger adults. The larger non-decision time could indicate that stimulus encoding (Madden et al., 2009) and/or motor processes (Voss et al., 2004; Ratcliff et al., 2006a) are slower in older than younger adults; it could also be that task preparation takes longer in older than younger adults (Karayanidis et al., 2009; Schmitz and Voss, 2012, 2014). Other than threshold separation and non-decision time, drift rate did not differ between the age groups; that is, the quality of the accumulated evidence was of similar size in older and younger adults. This is in line with other aging studies, where drift rate has been found to be similar for younger and older adults across a wide range of tasks, such as signal detection tasks

(Ratcliff et al., 2001), lexical decision tasks (e.g., Ratcliff et al., 2004), or item recognition memory tasks (e.g., Ratcliff et al., 2010, 2011; Ratcliff and McKoon, 2015). Interestingly, older adults differ from children in this respect, with children showing smaller drift rates than young adults in lexical decision (Ratcliff et al., 2012) and task-switching (Schuch and Konrad, under review) paradigms. This suggests that evidence accumulation is noisier in children than young adults, but is of similar quality in young and older adults.

#### Task Inhibition

Regarding task inhibition, n-2 task repetition costs were obtained across both age groups in mean RT, mean log RT, and mean error rates, which did not differ statistically between older and younger adults, confirming previous findings (Mayr, 2001; Lawo et al., 2012). Diffusion model analysis revealed that the task inhibition effect was reflected in drift rate, in line with another study from our lab (Schuch and Konrad, under

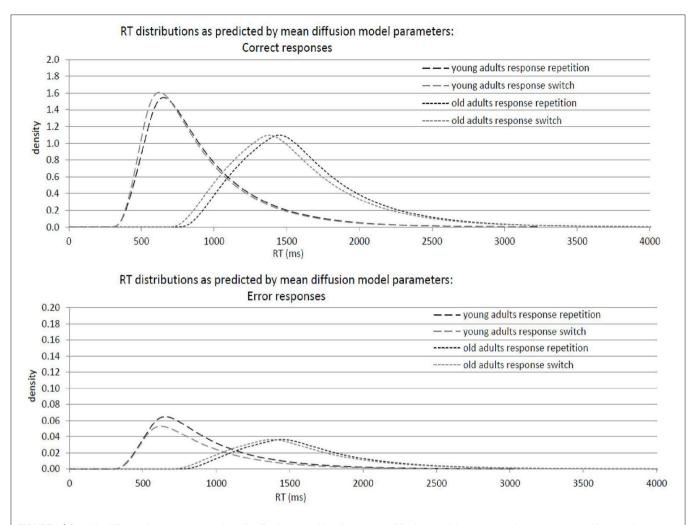


FIGURE 5 | Graphical illustration of response-time distributions resulting from mean diffusion model parameters in response repetitions and response switches in young adults (18–26 years; N=22) and older adults (64–79 years; N=22). Upper panel: Distribution of correct responses. Lower panel: Distribution of error responses.

review). Specifically, task inhibition was reflected in smaller drift rate in trials with more persisting inhibition (ABA) than in trials with less persisting inhibition (CBA), a finding fitting well with previous research suggesting that the task inhibition effect is mainly due to prolonged response selection in ABA relative to CBA trials (Schuch and Koch, 2003; Koch et al., 2010). This finding is also in line with diffusion-model studies of task-switching performance suggesting that carry-over effects from previous tasks affect drift rate (Schmitz and Voss, 2012, 2014). The inhibition effect in drift rate occurred in both age groups, and tended to be more pronounced in older than young adults. That is, the data clearly do not show a reduced inhibition effect in drift rate in older adults, as has been observed in children (Schuch and Konrad, under review), suggesting that inhibition of task-specific stimulus-response associations is at least as strong in older adults as in young adults.

Moreover, in the older but not the young adults, the task inhibition effect was also reflected in threshold separation and

non-decision time, with smaller threshold separation and larger non-decision time in ABA than CBA trials. This could possibly mean that older adults engage in more advance task preparation in ABA than CBA, task preparation continues after stimulus onset, leading to longer non-decision time in ABA than CBA. This increased task preparation in ABA than CBA might involve a lowering of the response thresholds, as is reflected in smaller threshold separation in ABA than CBA. That is, older adults might apply different strategies than younger adults when performing the task-switching paradigm.

Although still speculative at this point, it could thus be the case that the comparable task inhibition effect obtained by analysis of mean performance is based on different strategies in young and older adults. The particular strategy applied might depend on the experimental setting; for instance, if emphasized in the instructions that advance task preparation is essential for performing the experiment, older adults might follow these instructions more closely than younger adults, and might hence

TABLE 3 | Analysis of Task Inhibition and Response Inhibition: Results of the 2  $\times$  2  $\times$  2 ANOVAs with within-subjects variables Task Sequence (ABA, CBA) and Response Transition (Response Repetition, Response Switch) and between-subjects variable Age Group (young adults, older adults).

Dependent measure	Sequen	raction Ta: ice × Resp ransition		Interaction Task Sequence  × Response Transition  × Age Group			
	F <sub>(1, 46)</sub>	р	$\eta_p^2$	F <sub>(1, 46)</sub>	р	$\eta_p^2$	
MEAN PERF	ORMANCE						
RT	<1.0	n.s.		<1.0	n.s.		
Log RT	<1.0	n.s.		<1.0	n.s.		
Error Rates	2.33	=0.13	0.05	<1.0	n.s.		
<b>DIFFUSION I</b>	MODEL PA	RAMETER	S				
а	2.22	=0.14	0.05	<1.0	n.s.		
ν	<1.0	n.s.		<1.0	n.s.		
$t_0$	<1.2	n.s.		<1.0	n.s.		
s <sub>t0</sub>	<1.0	n.s.		<1.0	n.s.		

Only the interactions of interest are shown (two-way interaction of Task inhibition  $\times$  Response Inhibition; three-way interaction of Task inhibition  $\times$  Response inhibition  $\times$  Age group). Analysis including all participants (24 young adults, 24 older adults).

engage in more task preparation. Differences in strategy could also be a possible reason for diverging findings in the literature (cf. Koch et al., 2010).

## Response Inhibition

Regarding response inhibition, n-1 response repetition costs were obtained across both age groups in mean RT and mean log RT, but not in error rates. Response-repetition costs in mean RT tended to be larger in older than younger adults, but in mean error rates, they were smaller in older than younger adults. Diffusion model analysis revealed that response-repetition costs were reflected in non-decision time across both age groups, with longer non-decision time in response repetitions than switches. This is in line with the idea that in both age groups, persisting response inhibition slows down motor processes when this response needs to be executed again. (Although less likely, it is also possible that response inhibition slows down task preparation or stimulus encoding processes, given that the nondecision time parameter subsumes a whole range of cognitive processes, cf. Schmitz and Voss, 2012). No significant age differences in response-repetition costs were obtained in any of the parameters.

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## Conclusion

Analysis of mean RTs and error rates revealed reliable task inhibition and response inhibition effects, but no consistent agerelated differences in these inhibition effects, confirming previous studies. Diffusion model analysis revealed that persisting task inhibition slowed response selection, whereas persisting response inhibition slowed motor processes, in both older and younger adults. There was some preliminary evidence for strategic differences between young and older adults in dealing with persisting task inhibition; the older but not the young adults seemed to engage in more task preparation, and lower the response thresholds, in trials with persisting inhibition. No agerelated differences in response inhibition were obtained in any of the parameters. In sum, diffusion model analysis did not reveal any evidence for an inhibitory deficit in older adults; rather, inhibitory ability on the task and response level in older adults was at least as strong as in younger adults; if anything, older adults might apply different strategies for overcoming persisting inhibition.

#### **AUTHOR CONTRIBUTIONS**

SS planned and designed the study, programmed the experiment, analyzed and interpreted the data, and wrote the manuscript.

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#### SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fpsyg. 2016.01722/full#supplementary-material

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