TAKING A HANDS-ON APPROACH: CURRENT PERSPECTIVES ON THE EFFECT OF HAND POSITION ON VISION

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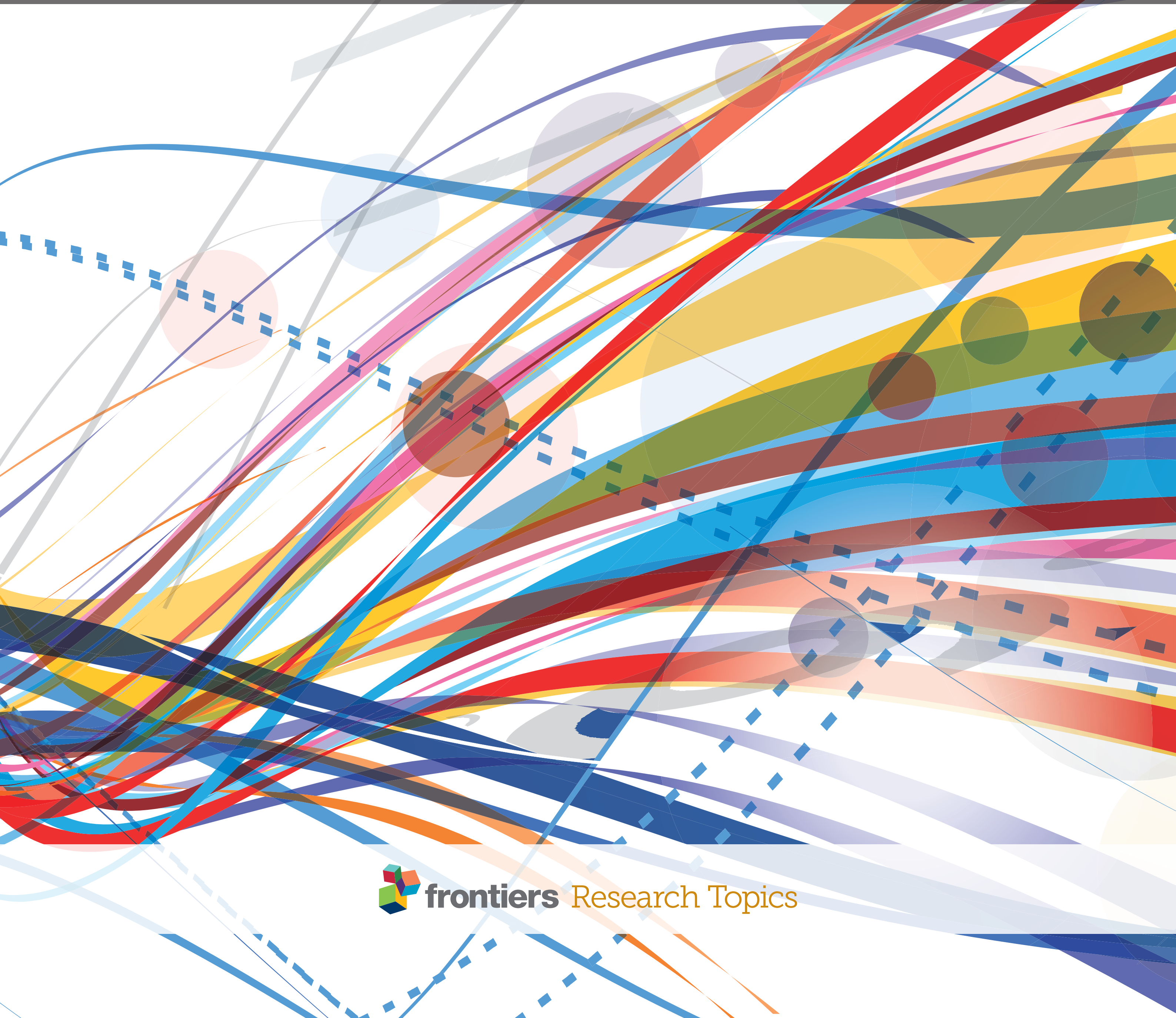

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TAKING A HANDS-ON APPROACH: CURRENT PERSPECTIVES ON THE EFFECT OF HAND POSITION ON VISION

Topic Editors:
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An exciting new line of research that investigates the impact of one's own hands on visual processing has flourished in the past several years. Specifically, several studies have demonstrated that objects near the hands receive prioritized attention, enhanced perceptual sensitivity, altered figure-ground assignment, prolonged and detail-oriented processing, and improved visual working memory. Taken together, these results demonstrate that the visual system reveals a new pattern of processing when one's hands are in proximity of viewed objects. Therefore, the vast majority of studies on visual processing, in which one's hands are kept away from the stimuli, may constitute but one side of a more complex story of the inner workings of the visual system.

With several consistent behavioral demonstrations of hand-altered vision now in the literature, the present challenge facing this growing field, and the aim of this Research Topic, is four-pronged: 1) Isolate and elucidate the underlying cognitive and neural mechanisms of hand-altered vision; 2) Map the parameters and conditions of hand-nearness that permit/prevent the onset or maintenance of hand-altered vision; 3) Determine the consequences of hand-altered vision for higher-level cognition and assess its applied potential (e.g., as a neuropsychological intervention); and, 4) Present a cohesive and predictive theoretical account of hand-altered vision.

We welcome submissions that fit into any one (or a combination) of the above domains. For behavioral research, we particularly encourage submissions that are relevant to the advancement of our understanding of the neural mechanisms of hand-altered vision (e.g., demonstrations that might corroborate or disconfirm proposed neural systems).

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EDITORIAL
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Editorial: Taking a hands-on approach: current perspectives on the effect of hand position on vision

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Keywords: embodied cognition, multisensory integration, perception and action, affordance, proprioception

Over the past 10 years, perception scientists have uncovered a surprising connection between people's vision and their hands. There is now compelling evidence that how people perceive, attend to, think about, and remember visual information depends on how close they have their hands to that information. With their hands near, people perform figure-ground assignment more efficiently, parse temporally adjacent events more precisely, and hold more information in visual working memory. Near their hands, people also detect sudden visual onsets more quickly, but search through arrays of items more slowly, and take longer to switch between different ways of interpreting the same perceptual content (e.g., "seeing the forest" vs. "seeing the trees"). These are but some of the ways in which visual processing changes when people's hands are in proximity of viewed information—a host of effects that we refer to here, collectively, as hand-altered vision (HAV).

The first decade of research into HAV has generated a substantial amount of new knowledge, which we recently reviewed in contemporaneous papers (Tseng et al., 2012; Brockmole et al., 2013). We subsequently established this Research Topic as a bridge to the next era of HAV research, through which we aimed to gather perspectives from across the research literatures on human action and peripersonal space representation. All told, the work here consists of 12 articles from 34 researchers who represent 23 institutions worldwide. Thanks to the efforts of our contributors, our scientific understanding of HAV has progressed along several major channels.

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Visual Attention Near the Hands: Mechanisms, Modulating Factors, and New Directions

The research literature on HAV began in earnest with two key findings about visual attention. First, people tend to prioritize their attention to visual signals in near-hand space over other locations (*prioritization effect*). Second, people are slower to disengage their attention from locations near their hands (*disengagement effect*). Considering the practical implications and potential applications of these effects, there has been a critical need for research into how and under what conditions hand-altered attention works. The following studies make considerable strides toward meeting that need.

We begin with a landmark study into the neurophysiological bases of near-hand effects on attention. Utilizing a combination of behavioral methods and neuroimaging (electroencephalography), Reed et al. (2013) found converging evidence for the existence of a prioritization effect and a disengagement effect during early and later stages of processing, respectively. Moreover, by capturing the neural signatures of these effects in the same perceptual episode, this work puts forth the most precise and comprehensive picture to date of hand-altered attention as it unfolds in real-time.

We also gain new insight into the factors that modulate hand-altered attention. To start, we learn that grasp posture makes a difference for the prioritization effect. As Thomas' work (2013) shows, people are more likely to prioritize locations near their hands when their hand posture affords a task-appropriate action (Thomas, 2013). We also learn that the disengagement effect may not be immune to one's recent postural history. Evidence of this comes from Schultheis and Carlson (2013). The more hand positions they tested within a single experimental session (visual search), the less likely their participants were to exhibit the typical disengagement effect. Finally, we see that different components of hand-altered attention may not necessarily be modulated by the same factors. Preliminary evidence of this stems from Vatterott and Vecera's study (2013), in which participants did not exhibit a prioritization effect but did show a disengagement effect during visual search (Vatterott and Vecera, 2013). Although the reasons for this dissociation are not yet clear, the results are consistent with the notion that prioritization of near-hand space was disrupted by certain unique features of the testing paradigm.

To conclude this section, we are pleased to present works that push the study of hand-altered attention into contexts considerably more complex than is typical in HAV research. Nearly, every study of hand-altered attention to date has involved participants seated at a computer while holding their hands at a fixed location either near to or far from the test stimuli. By contrast, many real-world tasks of visual attention involve the coordinated use of both hands in different states of activity, as when slicing a cucumber or using a smartphone. How do people prioritize their attention in scenarios like these? Thanks to Festman et al. (2013), we now have a clearer understanding of hand-altered attention as a product of both the static and dynamic features of the hands working in conjunction. The question of coordination in visual attention also applies to social contexts, as when two people work together on a jigsaw puzzle. What role do *other people's* hands play in shaping how people allocate their own attentional resources? Thanks to Sun and Thomas (2013), we now understand that people can and do prioritize the space near a friend's hand following a collaborative joint-action task.

Visual Perception Near the Hands: Biases and Theories

As a field, we have made significant progress into understanding what HAV is and how it works by documenting the variety of mental processes that are affected by hand-proximity. Quite often, the reported effects have taken the form of biases or tradeoffs in visual processing that correspond with relative hand placement. The utility of identifying these biases lies in what they can tell us about the neural mechanisms that give rise to HAV.

Two studies in this Topic report processing biases that imply a strong right-hemisphere involvement in near-hand effects. First, Langerak et al. (2013) show that people preferentially process global vs. local information near their left hand but not their right. Second, in a study that considers near-hand effects on auditory processing, Tseng et al. (2014) find that hand-proximity elicits faster tone localization to the left, with no such advantage to the right. In both cases, evidence of right-hemisphere involvement supports the *parietal lobe account* of HAV, which attributes near-hand effects to (right) parietal mechanisms involved in multisensory integration and body-space coding. Such evidence is also consistent with the newly emerging *magnocellular account* of HAV. According to this account, hand-proximity biases visual processing along the action-oriented magnocellular dorsal pathway, which incidentally also includes the parietal lobe and favors motion, location, and low spatial frequency (LSF) information over color, detail, and high SFs. It follows, then, that people ought to be better at LSF tasks near their hands, and Chan et al. (2013) show evidence of this through enhanced gist processing. It also follows that magnocellular biases ought to be reflected in how people remember information near their hands. In support of this, Kelly and Brockmole (2014) report a dissociation in people's working memory capacity for orientation (+) vs. color (−) information that corresponds to hand-proximity.

Theories of HAV generally agree that the purpose of HAV is to facilitate interaction with the environment. This is consistent with other research literatures that have also found evidence of specialized mechanisms for supporting interaction. As one example, perceiving visual content that contains action-relevant information primes the motor system for action. Here, Wilf et al. (2013) show that this effect is not purely cognitive nor driven by top-down biases, but rather can be detected in the muscles via electromyography at early stages of movement execution. As a second example, tools can become incorporated into the body schema at the cognitive and neural level. Furthermore, the space near the functional end of a tool is awarded many of the same processing advantages as near-hand space. Here, Brown and Goodale (2013) review the literature on near-tool effects, and they conclude that motor knowledge is critical for these effects to emerge.

In considering HAV in the context of affordances, tool-use, and the like, we notice something akin to a cycle. HAV helps us perceive action-relevant information in the environment; perceiving action-relevant information primes us to take action; if taking action results in taking possession of and wielding a tool, the body schema adapts accordingly, and visual processing of near-tool space is altered to facilitate interaction; and so on.

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Attention's grasp: early and late hand proximity effects on visual evoked potentials

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Behavioral studies suggest that visual attention is biased toward stimuli in the region of space near the palm of the hand, but it is unclear whether this effect is universal or selective for goal/task-related stimuli. We examined event-related potentials (ERPs) using a visual detection task in which the hand was placed near or kept far from target and non-target stimuli that were matched for frequency and visual features to avoid confounding factors. Focusing on attention-sensitive ERP components, we found that P3 (350–450 ms) amplitudes were increased for Hand Near conditions for targets only, demonstrating a selective effect consistent with the P3's cross-modal and task-relevance influences. An N1 variant implicated in visuo-tactile integration (central Nd1; 120–190 ms) showed similar target-specific effects. P1 (80–110 ms) effects for target stimuli were also apparent, but may have applied to non-targets as well, which would be consistent with the P1's association with early, pre-categorical increases in sensory gain. Collectively, these findings suggest that by the time stimuli are categorized as relevant/irrelevant for action, the proprioceptive effects of the hand on visual attention are selective for goal/task-related stimuli. At the same time, hand proximity appears to bias attention early, starting with a facilitation of processing for perhaps any visual stimuli near the hand, and continuing with enhancements that are selective to those stimuli categorized as task-relevant.

Keywords: attention, multisensory, bimodal, visuo-tactile, event-related potentials (ERPs)

The embodied view in cognitive science focuses on how the functional capabilities of the body influence information-processing (Wilson, 2001). For example, the hands may have an impact on attention because they are the main effectors by which we interact with the world. The region of space near the palm represents a more likely candidate for action than other locations, and as such may command a disproportionate share of attentional resources (Reed et al., 2007). Behavioral studies have demonstrated such attentional biases (Reed et al., 2006, 2010; Abrams et al., 2008; Cosman and Vecera, 2010; Tseng and Bridgeman, 2011), but it is unclear at what stage of cognitive processing hand proximity becomes influential for spatial attention and how it affects processing. These questions are well-suited to an electroencephalography (EEG) approach, which has the temporal resolution necessary to reveal when stimuli near the hand receive increased neural resources. In this study, we examined event-related potentials (ERPs) to target and non-target stimuli presented near and far from the hand to determine whether having stimuli in grasping space facilitates attention for all stimuli in the same manner or whether some effects are selective to goal/task-relevant stimuli.

In two covert orienting studies, Reed and colleagues demonstrated a facilitation of processing for targets in grasping space, even when hand position was unrelated to task demands (Reed et al., 2006, 2010). For example, in covert orienting tasks, participants detected the onset of targets at peripheral locations of a computer screen more rapidly when the hand was held up near that location than when the hand was held away. This effect occurred even when the hand was visually occluded, but was eliminated when an arbitrary visual anchor (a board) was placed next to potential target locations instead of the hand (Reed et al., 2006). Thus, these results suggest that it is not the visual stimulus of the hand, but rather tactile/proprioceptive information about hand position that affects the processing of visual targets in grasping space. Nonetheless, behavioral studies cannot definitively determine at what stage of processing such visual and tactile/proprioceptive sensory integration occurs.

Some behavioral studies suggest that the hand's influence occurs early in processing (Abrams et al., 2008; Cosman and Vecera, 2010). Hands positioned close to the location of a visual stimulus can slow the shifting of attention away from that location in a variety of attention tasks, such as covert attention, inhibition of return, and attentional blink tasks (Abrams et al., 2008), and can improve visual short-term working memory (Tseng and Bridgeman, 2011). Hand proximity also affects figure-ground segregation, a process thought to occur early in visual processing (Cosman and Vecera, 2010). When participants placed either their hand or a wooden dowel on one region of two-color ambiguous figure, the region near the hand, but not the dowel, was more likely to be perceived as an object than background. Such studies demonstrate the integration of visual inputs with tactile and proprioceptive inputs for stimuli appearing in grasping space. In these studies, the conditions under which hand bias is found are consistent with those recording from visuo-tactile bimodal neurons in non-human primate single-cell recording studies: These neurons respond to tactile stimuli on the hand as well as visual stimuli presented on or near the hand (Graziano and Gross, 1993; Graziano, 1999; Graziano and Cooke, 2006) and are located in cortical regions that support a multimodal system for upcoming action: parietal cortex, premotor cortex, and the putamen (Graziano and Gross, 1994; Fogassi et al., 1996; Duhamel et al., 1998; Graziano, 1999; Graziano and Cooke, 2006). These sensory effects are thought to occur early in sensory processing at pre-categorical levels.

Other studies demonstrate that hand position effects involve later, higher-order processing. For example, Davoli et al. (2010, 2012) have shown that hand-proximity can bias observers toward detail-oriented processing of nearby stimuli, although at the expense of general semantic processing. Garza et al. (2013) found a biasing effect of the hand on target detection when instructions emphasized the location of the hand held near targets but not when instructions emphasized the location of the other hand, which was used to make responses. Qian et al. (2012) found a biasing effect of the hand only when stimuli near it were task relevant. These studies suggest that hand presence itself may imply a task context, biasing participants' expectations as to where important stimuli may occur, but that top-down influences from instructions and task demands can likewise shape this context, ultimately improving the potential for functional interaction with objects.

Event-related potentials can reveal the time course and selectivity of hand position influences on visuospatial attention because we can look for an influence of the hand on ERP components known to reflect specific stages of cognitive processing. In this study, we used a target detection task designed to evoke a P3 as well as earlier components whose amplitudes could vary as a function of hand position. Thus, we focused on three attention-sensitive ERP components that have been implicated in both sensory and task-related aspects of visuo-tactile tasks: the P1, Nd1, and P3. The P1 (80–110 ms) is a positive deflection over lateral posterior regions of the scalp, reflecting the activity of extrastriate cortex generators (Hillyard et al., 1998). It has greater amplitude in response to stimuli at attended than unattended locations, and is thought to reflect early sensory gain control mechanisms. The Nd1 (150–200 ms) is a negative deflection and a variant of the N1, with a midline parietal distribution that has been implicated in visuo-tactile integration (Kennett et al., 2001). For instance, the Nd1 shows greater amplitudes in a cross-modal cuing task when visual and tactile stimuli were presented than when unimodal stimuli were presented. Likewise, a similar component was found to be enhanced when visual stimuli were presented on the hand for implicit "touch" as opposed to near the hand (Simon-Dack et al., 2009). Finally, the P3 (300–500 ms) reflects discrimination of stimulus categories at a more abstract, task or motivationally relevant level. It is typically maximal over centroparietal regions and is produced by a number of neural generators and cognitive factors including allocation of attentional resources and categorization of events (Kok, 2001). The P3 response to stimuli can vary by category at a very high level, for instance on the basis of high vs. low motivational value (e.g., Leland and Pineda, 2006, 2011).

Specifically, to investigate when and how attention is biased toward space near the hand, we used a visual target detection task in which the hand was placed near or held far from target and non-target stimuli. Targets appeared with the same frequency as non-targets (50/50) and the stimuli were counterbalanced across subjects with respect to which shapes served as targets and which served as non-targets. The matching of targets and non-targets for frequency and visual features is critical to the paradigm because it allows us to determine, without confounding factors, whether hand effects on ERP components are selective to targets or apply to non-targets as well. The P3 is thought to reflect post-categorical processing and is sensitive to motivation and task-demands. If visual stimuli appearing near the hand evoke relatively larger P3 components, we would expect larger or exclusive hand effects for target stimuli as compared with non-target stimuli. The Nd1 is an early component that is not clearly pre- or post-categorical but appears to be sensitive to cross-modal influences. Given prior findings of cross-modal effects on N1-type components, we would predict that the Nd1 would show enhancement effects of hand proximity that may or may not be selective for target stimuli. Finally, because the P1 is thought to reflect early sensory processing at pre-categorical levels, if visual stimuli appearing near the hand evoke relatively larger P1 components, we expect these hand effects to be observed for both target and non-target stimuli.

METHODS

PARTICIPANTS

Nineteen healthy right-handed participants (12 male, age = 20.22, *SD* = 2.95 years) completed the experiment for partial course credit. All reported normal or corrected-to-normal vision and none reported previous head trauma. The experiment was approved by the Claremont McKenna College and Scripps College Institutional Review Boards. Two participants' data were excluded from analyses due to excessive artifact.

STIMULI AND APPARATUS

Stimuli were presented on a 17″ CRT monitor via a PC computer using E-Prime 1.1 software (Psychological Software Tools, Pittsburgh, PA). Responses were recorded by a PSTnet SRbox. Fixation consisted of an 8.5 × 8.5 cm dotted gray cross against a black background. Target and non-target stimuli were 2 × 2 cm yellow boxes with a 0.5 cm gap centered on either the top or the bottom border of the box against a black background. One gap location was used for targets and the other for non-targets, counterbalanced across participants. All fixation crosses and stimuli were presented at vertical center and approximately 10 cm in from the left or right side edge of the display. This allowed the left or right hand, respectively, to be placed on the plastic edge of the display monitor so that stimuli appeared near the palm, within grasping space (**Figure 1**). Using a Thor Laboratories Optical Power Meter (model PM100) with a S130A (400–100 nm) sensor meter held 2.54 cm in front of the monitor screen, we established that targets and non-targets registered the same power (108 mW; "mW" = milliwatts or dBm of optical power), which was higher than that for the fixation (87 mW). When the sensor was held 2.54 cm in front of the plastic edge of the monitor while fixations and stimuli alternated, we established that the sensor reading (10 mW) did not change, regardless of whether the hand was near the plastic edge of the screen or not.

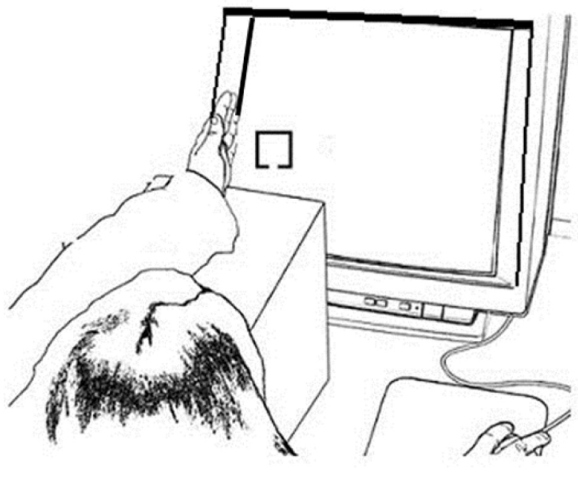

FIGURE 1 | Example experimental setup for the Hand Near stimulus Left condition. The left hand was held on the edge of the monitor screen edge and the left fixation and stimulus appears on the left side of the screen close to the hand; the right hand responded to the target.

PROCEDURE

Participants sat in a darkened room with their heads 50 cm from the display. Their body and shoulders were positioned square to the screen so that body midline was aligned with the center of the screen. They performed a target detection task in which 50% of trials were targets and 50% of trials were non-targets (**Figure 2**).

Hand position and stimulus side varied to create four conditions (Hand Near Left, Hand Near Right, Hand Far Left, Hand Far Right): Stimuli were presented either on the left or right side of the screen and the same-side hand was placed either near or far from the stimulus location (e.g., the left hand was held near or far from the left stimuli and the right hand was held near or far from the right stimuli). The index finger of the opposite-side hand was used to make button presses. For each block, participants either placed one hand on the edge of the monitor next to the fixation cross with the thumb directed up in a relaxed grasping position (Hand Near), or placed the hand in the lap (Hand Far). In Hand Near conditions, participants rested their elbows on a cushion and relaxed their arms and shoulders. To equate visual inputs for the two conditions, participants performed the task in a fully darkened room and, in the Hand Near conditions, placed their hands on the plastic edge of the monitor. Although previous behavioral and EEG studies have documented bias effects of hand proximity on performance when the hand is visible as well as when the hand is not visible (Reed et al., 2006; Garza et al., 2009), the experiment was conducted in a dark room so that participants could not see their hands and the light from the stimuli displayed on the monitor did not illuminate or reflect off the hand and arm.

Trials began with the appearance of a lateralized fixation cross. After a variable SOA of 2000–3500 ms, a stimulus appeared for

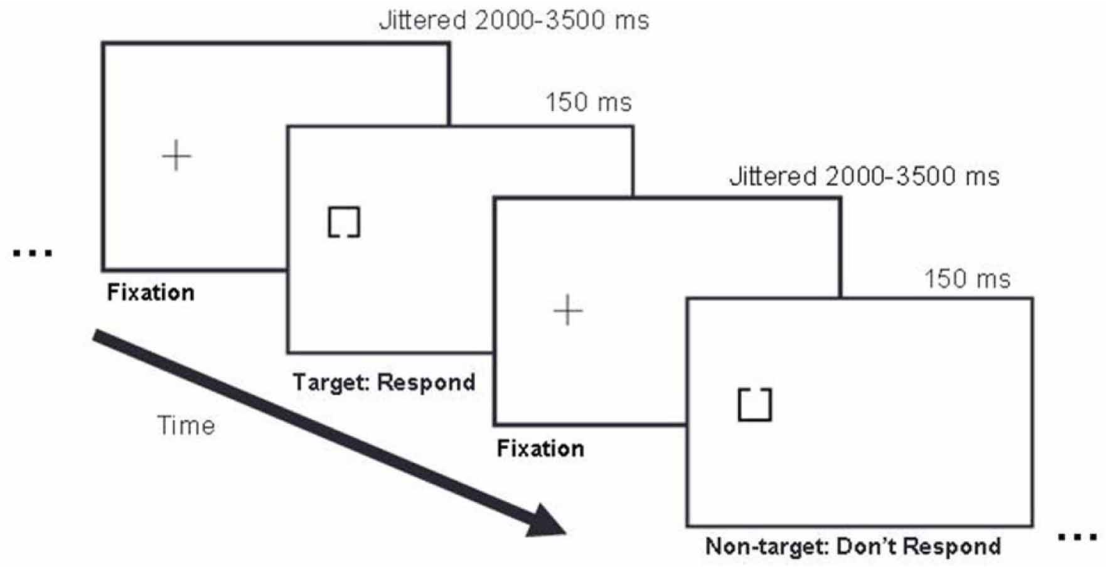

FIGURE 2 | Example trial sequence. In this left stimulus side example, a fixation cross appeared on the left side of the display for 2000–3500 ms, followed by either a target or non-target stimulus presented for 150 ms, followed by the next fixation cross presented for 2000–3500 ms, and the next stimulus for 150 ms, and so on. Targets and non-targets appeared with equal probability (50/50) in pseudo randomized order.

150 ms at the center of the cross. Participants pressed a response key with the index finger of the opposite hand if a target appeared. Following the response, or after 2000 ms post-stimulus onset, the fixation re-appeared for the next trial. Each type of block was presented four times, for a total of 16 blocks. Each block included 25 target trials and 25 non-target trials. Block order and trial order were pseudo-randomized so that two blocks of the same type could not follow each other and no more than four trials in a row occurred with the same stimulus type (target or non-target). Participants received feedback on performance accuracy at the end of each block and were given brief breaks between blocks.

ERP RECORDING

EEG was acquired using a high-impedance EGI 64-channel Hydrocel Geodesic EEG System (GES) 200 (Electrical Geodesic Inc., Eugene, OR, USA). The EOG was recorded from electrodes located above and below each eye. The EEG sampling frequency was 250 Hz with a hardware band-pass filter from 0.1 to 100 Hz. Impedances were kept below 80 Ω.

EEG and EOG data were processed off-line using NetStation 4.4.2 (Electrical Geodesic Inc., Eugene, OR, USA). Data were filtered with a 35 Hz low-pass filter. Continuous data were segmented from −100 ms pre-stimulus onset to 800 ms post stimulus onset for eight conditions: 2 (Hand Near, Hand Far) × 2 (left, right) ×2 (target, non-target). Only data from correct trials were analyzed. Data were visually inspected for blinks and eye-movements after an automatic artifact rejection criterion of ±140 μV was applied from –100 pre-stimulus onset to 800 ms post-stimulus onset. NetStation's Ocular Artifact Removal tool (Gratton et al., 1983; Gehring and Foote, 1996) was used with a blink slope threshold of 13 μV/ms to correct and remove ocular artifact. Surviving trials were averaged by condition relative to a baseline of −100 to 0 ms. Data were re-referenced using an average reference.

RESULTS

RESPONSE TIME ANALYSES

Mean response times (RTs) for correct target trials were calculated, excluding misses and trials with RTs outside of a window of 200–650 ms to factor out preemptive responses or inattention errors, as in Reed et al. (2006, 2010) and Garza et al. (2013); fewer than 1% of trials were excluded. To evaluate the effect of hand position on target RTs, a repeated-measures hand position (2: Hand Near, Hand Far) × stimulus side (2: left, right) analysis of variance (ANOVA) was conducted. Participants responded faster for targets near the hand than targets far from the hand [$F_{(1,\ 16)} = 6.44$, $p = 0.022$, $\eta_p^2 = 0.29$; **Figure 3**]. No main effects were found for hand side or the hand position by hand-side interaction (p's > 0.31).

ERP ANALYSES

Electrode sites are identified using the international 10–10 system (**Figure 4**). Electrode clusters and latency windows were chosen based on those reported in visuo-tactile multisensory integration studies (Kennett et al., 2001; Simon-Dack et al., 2009), visual attention studies (Eimer, 1994), and from an examination of where deflections were most prominent in the grand average waveforms sites from the current data set: P1 (80–110 ms) for lateral parietal-occipital sites (O1/P1/P3; O2/P2/P4), central Nd1 (120–190 ms) for midline parietal-occipital sites (Pz/POz), P3 (350–450 ms,) and a late positivity referred to as the P3Termination or P3T (450–650 ms) for lateral central-parietal sites (FC1/C1/CP1; FC2/C2/CP2). Mean amplitude values were calculated within specified time windows.

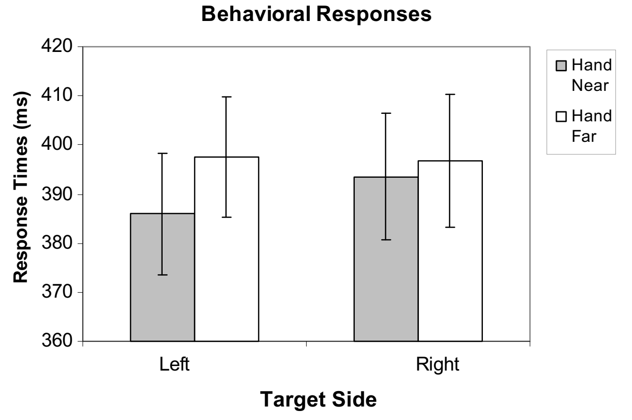

FIGURE 3 | Mean response time data for Hand Near and Hand Far conditions for targets appearing on left and right sides of the display. Error bars represent standard error.

Within-subjects ANOVAs were conducted for each ERP component and for target and non-target stimuli, using the following factors: hand position (2: Hand Near, Hand Far), stimulus side (2: Left, Right), and, for the lateralized P1, P3 and P3T components, cluster location/hemisphere [2: Left Hemisphere (LH), Right Hemisphere (RH)].

P1 Analyses

Targets. For targets, a significant hand position × stimulus side × cluster interaction revealed generally larger P1 amplitudes in electrode clusters contralateral to target side, and greater P1 deflections in RH electrode clusters for left targets in the Hand Near condition [$F_{(1,\ 16)} = 5.13$, $p = 0.04$, $\eta_p^2 = 0.24$; **Figure 5**]. *Post-hoc* comparisons confirmed a significant hand position difference for left-side targets in the contralateral RH cluster [$t_{(16)} = 2.87$, $p = 0.01$], but not for other hand position comparisons (p's > 0.13). No other main effects or interactions were found (all p's > 0.09).

Non-targets. A significant hand position × stimulus side × cluster interaction was found for non-targets [$F_{(1,\ 16)} = 4.44$, $p = 0.05$, $\eta_p^2 = 0.22$; **Figure 5**]. A stimulus side main effect indicated larger amplitudes for left-side relative to right-side non-targets [$F_{(1,\ 16)} = 5.23$, $p = 0.04$, $\eta_p^2 = 0.25$]. Also, a stimulus side × cluster interaction showed larger P1 deflections for clusters contralateral to stimulus side [$F_{(1,\ 16)} = 10.34$, $p = 0.005$, $\eta_p^2 = 0.39$]. *Post-hoc* comparisons indicated a trend for larger P1 amplitude in the Hand Near than Hand Far condition for

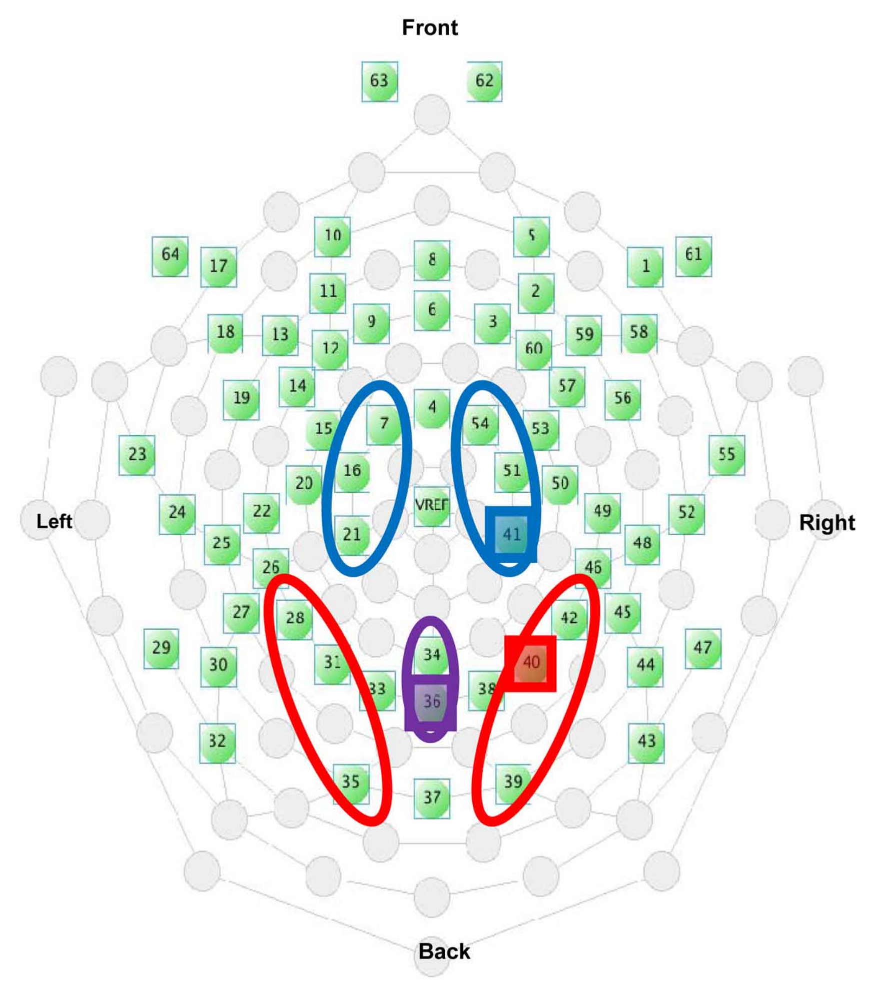

FIGURE 4 | Electrode selection from the EGI 64-channel Hydrocel net. The highlighted electrodes indicate the placement of the representative electrodes used in **Figures 5B**, **6B**, and **9**.

left-side targets in the contralateral RH cluster [$t_{(16)} = 1.73$, $p = 0.10$]. A larger negative deflection was found in the Hand Far than Hand Near condition for right-side non-targets in the ipsilateral RH cluster [$t_{(16)} = -2.70$, $p = 0.02$], but it does not fit the pattern established by our other results, which overall show a larger effect for stimuli near the hand and/or over the hemisphere contralateral to the stimulus (for lateralized potentials). No other Hand Near/Far comparisons were significant (all p's > 0.29). No other main effects or interactions were found (all p's > 0.11).

Nd1 Analyses

Targets. A hand position × stimulus side ANOVA for the Nd1 site (Kennett et al., 2001) revealed a significant hand position effect for target stimuli [$F_{(1,\ 16)} = 4.90$, $p = 0.04$, $\eta_p^2 = 0.23$; **Figure 6**], showing greater deflections for Hand Near compared to Hand Far conditions. A stimulus side effect indicated greater Nd1 amplitudes for targets appearing on the left than targets on the right [$F_{(1,\ 16)} = 4.49$, $p = 0.05$, $\eta_p^2 = 0.22$]. There was no interaction [$F_{(1,\ 16)} < 1$, $p = 0.49$, $\eta_p^2 = 0.03$].

Non-targets. For non-target stimuli, no main effects or interactions reached significance (all p's > 0.28; **Figure 6**).

P3 Analyses

Targets. A significant hand position × stimulus side × cluster interaction indicated larger positivities in the RH electrode clusters overall, but also larger contralateral positivities for the Hand Near condition, especially in the LH electrode clusters [$F_{(1,\ 16)} = 11.60$, $p = 0.004$, $\eta_p^2 = 0.42$; **Figures 7, 9**]. *Post-hoc* t-tests showed significant hand position differences in the contralateral hemisphere [right target/LH $t_{(16)}= 2.36$, $p = 0.03$; left target/RH $t_{(16)} = 4.55$, $p < 0.0001$], but not the ipsilateral hemisphere [right target/RH $t_{(16)} = 0.66$, $p = 0.95$; left target/LH $t_{(16)} = -0.36$, $p = 0.72$]. The trend for hand position [$F_{(1,\ 16)} = 3.67$, $p = 0.07$, $\eta_p^2 = 0.19$] revealed a tendency for larger P3 amplitudes for Hand Near than Hand Far positions. There was a cluster side/hemisphere effect, suggesting greater P3 amplitudes in the RH than LH electrode clusters [$F_{(1,\ 16)} = 4.70$, $p = 0.05$, $\eta_p^2 = 0.23$]. The stimulus side × hemisphere interaction [$F_{(1,\ 16)} = 12.97$, $p = 0.002$, $\eta_p^2 = 0.45$] was mediated by the

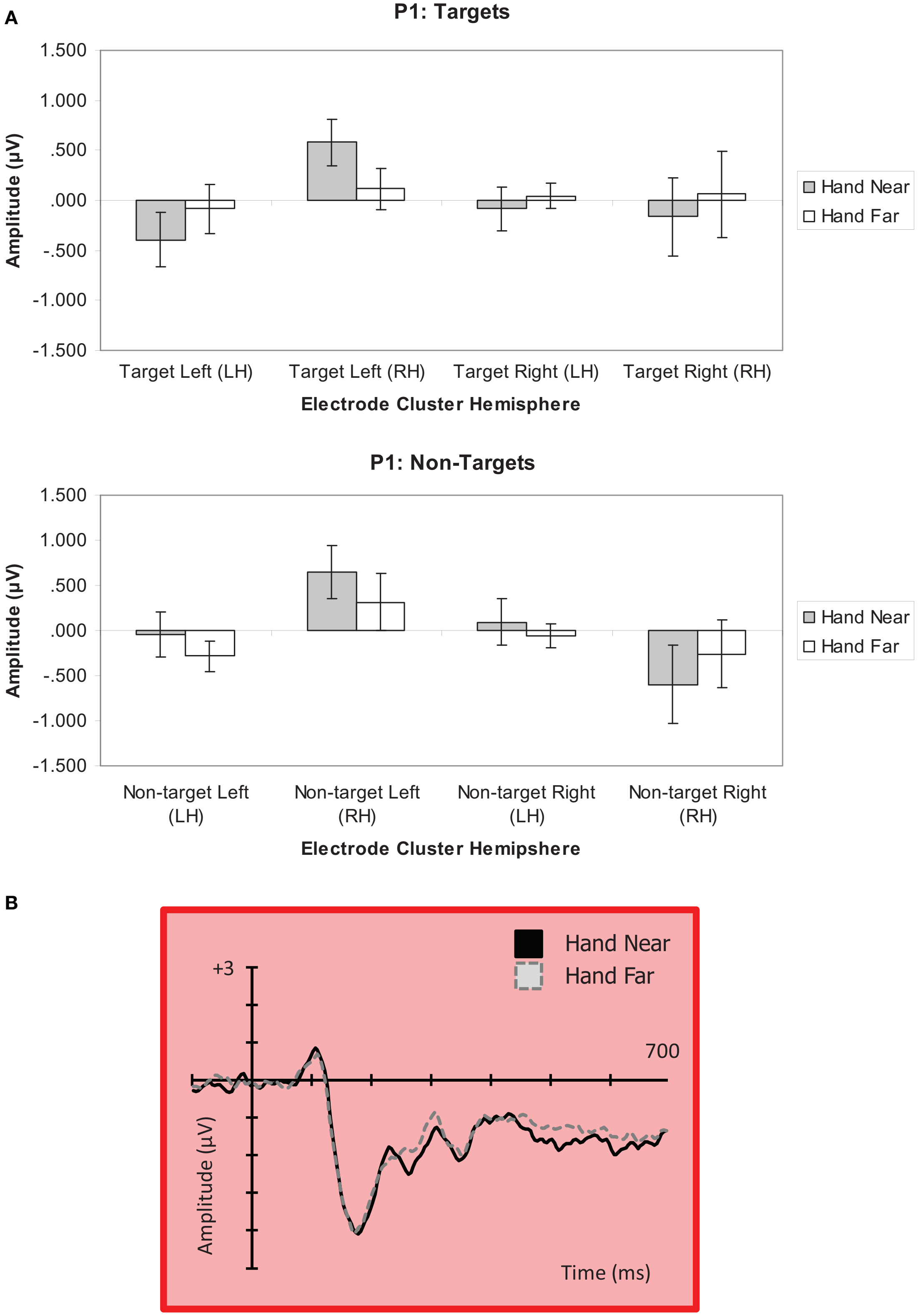

FIGURE 5 | (A) P1 (80–110 ms) mean amplitudes (μV) comparing Near and Far conditions for left- and right-side targets and non-target stimuli in left (LH) and right hemisphere (RH) electrode clusters. Error bars represent standard error. **(B)** Grand average waveform for the P1 at representative electrode site P2 in the contralateral right hemipshere. Voltage is plotted as a function of time, 100 ms pre-stimulus onset to 700 ms post-stimulus onset. The left Near condition produced a significant effect in the right hemisphere.

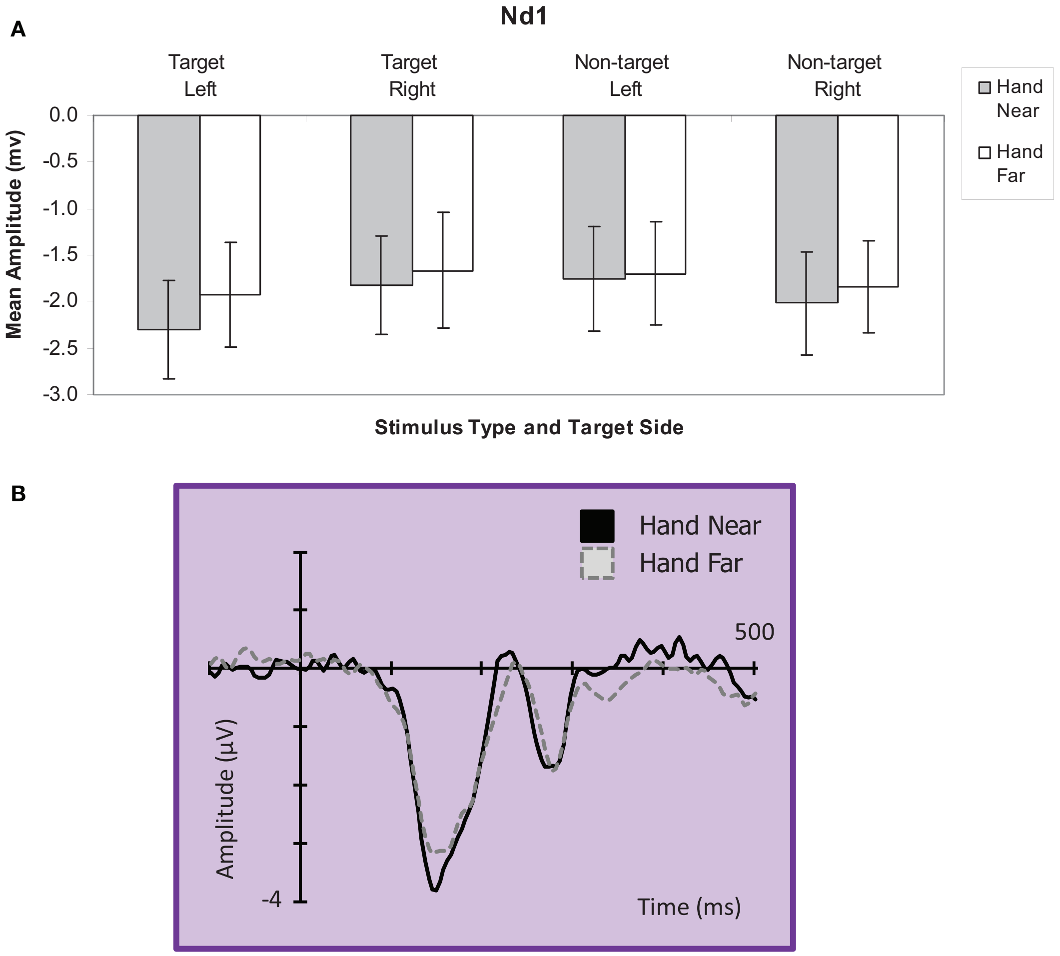

FIGURE 6 | (A) Nd1 (120–190 ms) mean amplitudes (μV) comparing Hand Near and Hand Far conditions for left and right-side target and non-target stimuli for the central electrode cluster. Error bars represent standard error. **(B)** Grand average waveform for the Nd1 at representative electrode site POz. Voltage is plotted as a function of time, 100 ms pre-stimulus onset to 700 ms post-stimulus onset. Compared to Hand Far conditions, Hand Near conditions produced a larger Nd1.

three-way interaction reported above. No effects were found for stimulus side, hand condition × stimulus side interaction, or the hand condition × hemisphere interaction (all p's > 0.63).

Non-targets. A marginal effect for cluster side/hemisphere [$F_{(1,\,16)} = 3.39$, $p = 0.08$, $\eta_p^2 = 0.18$] suggested greater amplitudes for RH over LH clusters (**Figure 7**). No other main effects were found [hand position: $F_{(1,\,16)} = 1.25$, $p = 0.28$, $\eta_p^2 = 0.07$; stimulus side: $F_{(1,\,16)} = 2.58$, $p = 0.13$, $\eta_p^2 = 0.14$]. A stimulus side × cluster interaction indicated relatively larger amplitudes in the contralateral hemispheres [$F_{(1,\,16)} = 5.80$, $p = 0.03$, $\eta_p^2 = 0.26$], but none of the other interactions reached significance (all p's > 0.13).

P3T Analyses

Targets. A significant hand position × stimulus side × cluster interaction indicated that the hand had continued processing influences [$F_{(1,\,16)} = 11.19$, $p = 0.004$, $\eta_p^2 = 0.41$; **Figures 8, 9**]. Similar to the P3, the prolonged positivity showed greater P3T amplitudes the RH electrode clusters overall and for Hand Near conditions in the contralateral hemisphere relative to the Hand Far conditions. *Post-hoc t*-tests showed significant hand position differences in the contralateral hemisphere [right target/LH $t_{(16)} = 2.24$, $p = 0.04$; left target/RH $t_{(16)} = 3.43$, $p = 0.003$], but not the ipsilateral hemisphere [right target/RH $t_{(16)} = -0.95$, $p = 0.36$; left target/LH $t_{(16)} = 0.13$, $p = 0.90$]. There were no other significant main or interaction effects (all p's > 0.10).

Non-targets. A cluster side/hemisphere effect showed larger amplitudes for RH than LH clusters [$F_{(1,\,16)} = 6.82$, $p = 0.02$, $\eta_p^2 = 0.30$; **Figure 8**]. No other main effects and interactions were significant (all p's > 0.08).

DISCUSSION

The hand may capture attention because of its relevance to future actions. For many future actions it is important to know what stimuli to act upon and which ones to ignore. In

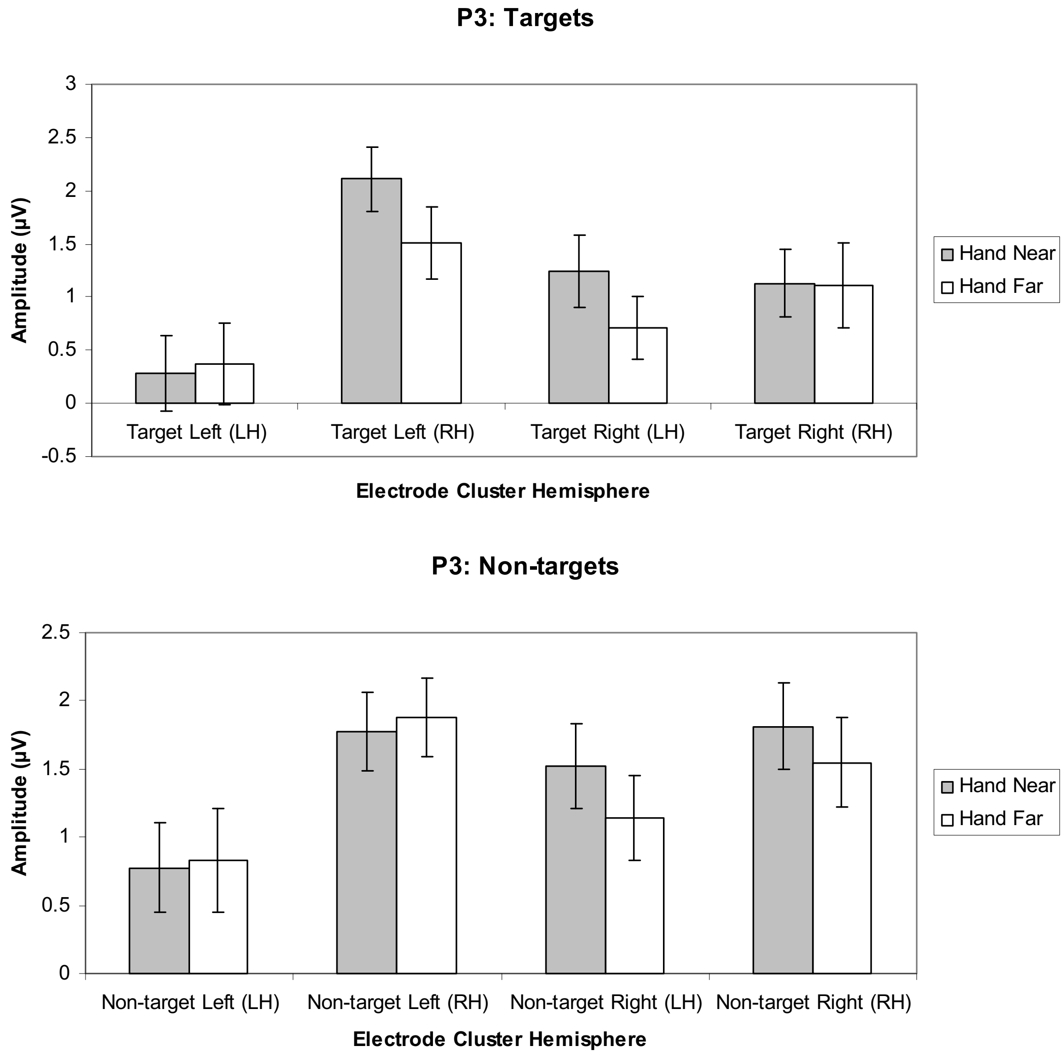

FIGURE 7 | P3 (350–450 ms) mean amplitudes (μV) comparing Hand Near and Hand Far conditions for left- and right-sided target and non-target stimuli in left (LH) and right hemisphere (RH) electrode clusters. Error bars represent standard error. For both left- and right-side targets, P3 amplitudes for the Near condition were larger relative to the Far condition in the contralateral hemisphere.

this study we examined behavioral and electrophysiological responses to characterize differential hand position influences on the neural processing of visual stimuli when they were and were not relevant to the task. We used a target detection paradigm in which non-target stimuli had the same probability and (through counter-balancing) visual features as target stimuli. The hand was placed either nearby, with the palm facing stimuli, or far away in the lap. Consistent with previous behavioral studies, RTs were facilitated for targets appearing near the hand compared to far from the hand. Nonetheless, the examination of hand position effects on the P1, Nd1, P3, and P3T ERP components demonstrated not only when but also the circumstances under which hand-related attentional biases occur. Distinguishing the neural signatures between target and non-target stimuli revealed the extent to which the hand's influence on processing was selective for goal/task-relevant stimuli as opposed to nonselective and applicable to all stimuli.

Our major ERP finding was that Nd1 and P3 amplitudes were modulated by the hand for target stimuli only; targets near the hand evoked larger potentials than targets far from the hand, but there was no difference for non-targets. The hand effect persisted late into the ERP (P3T: 450–650 ms). We also found evidence of a hand effect on the target-evoked P1 over the right hemisphere for targets presented on the left. There was a trend toward a similar effect for non-targets, which would be consistent with the P1 reflecting early visual processing before stimuli are discriminated as targets vs. non-targets. ERP effects in general showed a pattern of right hemisphere dominance. Collectively, these findings suggest that the hand enhances visuospatial processing over a wide temporal window, starting at the level of sensory processing as reflected by the P1 component and continuing with

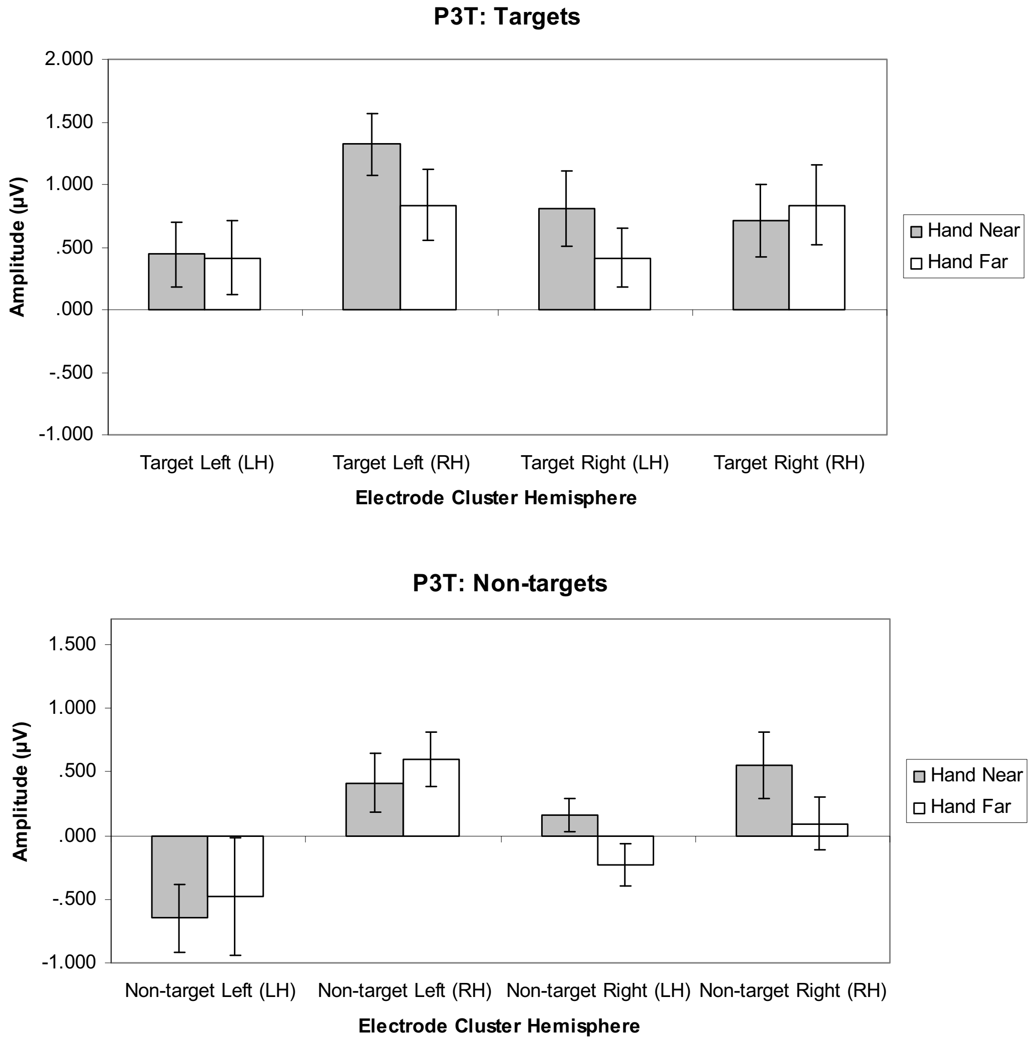

FIGURE 8 | P3T (450–600 ms) mean amplitudes (µV) comparing Hand Near and Hand Far conditions for left- and right-sided target and non-target stimuli in left (LH) and right hemisphere (RH) electrode clusters. Error bars represent standard error. For both left- and right-side targets, Near condition P3T amplitudes continued to be larger relative to the Far condition in the contralateral hemisphere.

higher levels of cognitive processing such as stimulus discrimination (Nd1) and evaluation (P3). This effect appears selective for goal/task-related stimuli once stimuli have been categorized as such, but it may apply non-selectively at earlier stages of processing.

An overall examination of the ERPs elicited in response to both target and non-target stimuli revealed enhanced amplitudes for stimuli presented near the hand, especially for electrode clusters contralateral to the hand and stimulus side. Generally, right hemisphere electrode clusters were more sensitive to hand position effects. This right hemispheric dominance for the earlier components may indicate a spatial processing advantage for the right hemisphere (Picton, 1992) and has been documented previously for spatial processing, as well as for the general distribution of attention (Weintraub and Mesulam, 1987).

The first hand-related effects were observed for the P1 (80–110 ms) component. Specifically, the P1 in the right hemisphere electrode cluster was amplified for left-side targets near the hand; there was little response in the left hemisphere electrode cluster for right-side stimuli. The P1 is often considered an index of sensory processing and encoding or sensory gain (Naatanen and Picton, 1987; Naatanen, 1992). It has also been interpreted as a reflection of focused attention (Hillyard and Anllo-Vento, 1998; Martinez et al., 1999). There was also a trend for a P1 effect for non-targets that matched the one found for targets (larger for stimuli near the hand, shown on the left side, contralateral and thus over the right hemisphere). Overall, the influence of hand position on P1 amplitudes for both targets and non-targets on the P1 could suggest that the hand has an early, pre-categorical effect on sensory gain and/or attention. A possible mechanism for this effect may be contributions from bimodal neuron populations that respond to visual stimuli near the hand (e.g., Graziano and Cooke, 2006). In non-human primates, these visuo-tactile bimodal neurons have hand-centered receptive fields

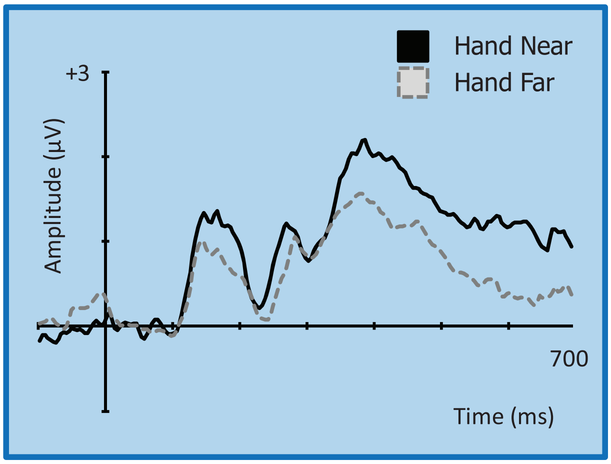

FIGURE 9 | Grand average waveform for the P3 (350–450 ms)/P3T (450–600 ms) for left-side targets at representative electrode site CP2 in the contralateral right hemisphere. Voltage is plotted as a function of time, 100 ms pre-stimulus onset to 700 ms post-stimulus onset. Compared to Hand Far conditions, Hand Near conditions show an amplification of the P3 component and a greater sustained positivity for the P3T, especially in the contralateral hemisphere.

and respond both to tactile stimuli and visual stimuli near the hand (Graziano, 1999). Bimodal neurons in conjunction with visual neurons could facilitate visual processing by encoding the same spatial location, but would not differentiate targets and non-targets.

Although bimodal neurons have been postulated to explain behavioral hand effects (e.g., Reed et al., 2006), our finding of a contralateral P1 effect for left-side targets (and possibly non-targets) but no left hemisphere effects suggests that potential bimodal neuron effects are a weak effect at best in our experiment. Experiments designed to emphasize early visual components may produce stronger evidence for this mechanism. However, our results point to other mechanisms contributing to hand-related effects. For instance, stronger amplitudes overall in the right hemisphere support a right-hemisphere dominance for spatial processing (e.g., Hugdahl, 2013; Reed et al., 2009). In addition, hand-related effects appear to be more robust later in processing. A recent EEG study by Qian et al. (2012) that examined hand position effects on the visual evoked potential (VEP) also did not find hand-related effects on the P1, but instead found them slightly later with the P2. When both hands were up to either side of a screen (as opposed to down on the desk), the P2 was attenuated for stimuli but only in the regions of space where targets could appear. Similarly, the later components we examined (Nd1, P3) showed hand effects that were restricted to task-relevant conditions, which in our case was based on stimulus features distinguishing targets and non-targets.

We observed hand-related amplification of the central Nd1 component (120–190 ms) for both left- and right-side stimulus conditions. The Nd1 has been interpreted as an index of attentional selection and multisensory integration (Kennett et al., 2001). Specifically, increased negativities were observed for targets appearing near the hand. This amplification suggests that tactile and proprioceptive inputs regarding hand location may be integrated with inputs from the visual stimulus. This slightly later component has been associated with multisensory integration in which physical tactile stimulation occurred with congruent visual stimulation or the viewing of the limb (Spence et al., 1998; Kennett et al., 2001; Taylor-Clarke et al., 2002). Simon-Dack et al. (2009) proposed that hand-related N1 effects could reflect the operation of visuo-tactile bimodal neurons as a mechanism to help integrate multimodal sensory information in peripersonal space (Graziano and Cooke, 2006). However, our comparison of both targets and non-targets suggests a different mechanism. Our results showed hand position effects for the Nd1 for targets only, indicating that stimulus classification had already occurred. The implicit relevance of hand location relative to visual targets may bias the system toward visuo-tactile integration in a top-down fashion. In sum, the Nd1 findings indicate that by the time stimuli are discriminated, the hand effect becomes selective for attended or action-relevant stimuli (targets).

Hand position not only affected early ERP components, but also the later P3 (350–450 ms) and possibly P3T (450–650 ms) latency ranges. The P3 is typically elicited in detection tasks for which targets are presented infrequently among frequent non-target stimuli (Polich, 2007). In our study, targets and non-targets were equally frequent. Although the P3s did not appear to be as large as for paradigms with rare targets, we found that hand position modulated P3 deflections for targets but not non-targets. This indicates that hand position has a more abstract, post-categorical effect on later visual processing. This is consistent with the observation that selected stimuli near the hand receive improved processing even when hand-proximity is imagined (Davoli and Abrams, 2009). Here we observed significantly larger P3 deflections when left-side or right-side targets were presented near the hand. The hand effect was strongest for electrode clusters contralateral to the target side. The P3 is associated with short-term memory maintenance and updating of target classification information (Picton, 1992) as well as attention and goal-related processing (Polich, 2007). Thus, target stimuli presented near the hand may enjoy attention, memory, and other cognitive benefits by a mechanism similar to that for stimuli that are infrequent, task-relevant, and/or motivationally salient. That this enhanced positivity appears to persist late into the ERP (P3T, 450–650 ms) may confer further advantages supporting effective action toward objects near the hand.

Collectively, our ERP findings suggest that the hand biases processing selectively for goal/task-relevant stimuli at later stages of processing. A bias is also evident at an early sensory/perceptual stage but at that point it may be non-selective (applying to target and non-target stimuli), which is to be expected if stimuli are not discriminated on the basis of such categories until later in processing. We interpret this as evidence of both non-selective pre-categorical effects and selective post-categorical effects of hand position. Although this may correspond to bottom-up and top-down influences, respectively, it is important to note that the block design of our study promotes an attentional set. That is, in the Hand Near condition the hand is up for the entire block and all stimuli appear in grasping space, providing a top-down influence of endogenously-driven attention throughout. Studies in which participants are told to attend to one region of space and not another (e.g., Chun and Wolfe, 2001) commonly show P1 (and N1) amplitude enhancements for attended space; these are effects at early stages of the visual response but reflect top-down attention.

A theory of embodied spatial attention implies that our bodies and our experience using them influence how attention is distributed in space and, as a result, how stimuli are processed. Our findings suggest such an influence for the hand both behaviorally and electro physiologically: stimuli appearing near the hand elicit faster response times and enhanced attention-related ERP components. This latter effect is evident at both early and late stages of processing, before and after stimulus categorization. Early detection for stimuli in general and prolonged facilitation of processing specifically for goal/task-relevant stimuli provide an effective combination allowing for more adaptive action toward objects in the environment that are most important and accessible.

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Grasp posture modulates attentional prioritization of space near the hands

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Changes in visual processing near the hands may assist observers in evaluating items that are candidates for actions. If altered vision near the hands reflects adaptations linked to effective action production, then positioning the hands for different types of actions could lead to different visual biases. I examined the influence of hand posture on attentional prioritization to test this hypothesis. Participants placed one of their hands on a visual display and detected targets appearing either near or far from the hand. Replicating previous findings, detection near the hand was facilitated when participants positioned their hand on the display in a standard open palm posture affording a power grasp (Experiments 1 and 3). However, when participants instead positioned their hand in a pincer grasp posture with the thumb and forefinger resting on the display, they were no faster to detect targets appearing near their hand than targets appearing away from their hand (Experiments 2 and 3). These results demonstrate that changes in visual processing near the hands rely on the hands' posture. Although hands positioned to afford power grasps facilitate rapid onset detection, a pincer grasp posture that affords more precise action does not.

Keywords: visual attention, visual processing near hands, power grasp, precision grasp, hand posture, embodied cognition

Objects that are within the reach of an observer present unique demands for visual processing. While visual attention allows for the selection of objects anywhere in the environment, only those items within peripersonal space afford immediate interaction, creating a need to integrate visual information with spatial, tactile, and proprioceptive representations. Observers process information near their hands differently than information presented far from their hands, experiencing changes in perception (Cosman and Vecera, 2010), attention (e.g., Reed et al., 2006; Abrams et al., 2008; Davoli and Brockmole, 2012) and memory (Tseng and Bridgeman, 2011; Thomas et al., 2013) (see Brockmole et al., 2013 and Tseng et al., 2012, for reviews). Investigators have suggested these changes in visual processing near the hands may assist observers in evaluating items that are candidates for action by enhancing analysis (Abrams et al., 2008; Tseng and Bridgeman, 2011; Davoli et al., 2012a), biasing for item-specific detail (Davoli et al., 2012b), altering representations of space via bimodal visuotactile neurons (Reed et al., 2006), or shifting information processing toward the action-oriented magnocellular visual pathway (Gozli et al., 2012).

The flurry of recent research on changes in visual processing of objects near the hands appeals to action-based explanations for why these changes occur, which raises the possibility that varying the affordances for action in a given situation may influence nearby-hand effects on vision. Observers detect targets more quickly when they are presented near the palm of the hand than the back of the hand or forearm, suggesting that processing changes occur specifically within the hands' grasping space (Reed et al., 2010). Similar results occur for targets presented near the functional end of tools (Kao and Goodale, 2009; Reed et al., 2010; Brown et al., 2011; Gozli and Brown, 2011), backing the notion that alterations in visual processing are tied to the potential for producing effective action. In addition, nearby-hand effects tend to drop off as the distance between the hands and the relevant visual stimulus increases (Tseng and Bridgeman, 2011; Adam et al., 2012). While this work points to the ties between action affordances and changes in visual processing near the hands, previous investigations have focused almost exclusively on comparing performance in visual paradigms under conditions in which participants either take hold of a display with both hands (e.g., Abrams et al., 2008) or hold a single open hand on one side of the display (e.g., Reed et al., 2006) against performance in conditions in which both hands are positioned away from the display. In these popular variations, observers position their hand(s) in a manner that affords a power grasp: the fingers function as a unit that can curl around an object to secure it against the palm. Although a few studies have also documented nearby-hand effects when observers position their hands below a display (Lloyd et al., 2010; Tseng and Bridgeman, 2011; Adam et al., 2012), even in these cases, the hands remain in a position with the fingers extended and held together.

Human hands possess a range of motion and action capabilities, from the rapid coordination of a rugby player catching a pass to the precision of a tailor threading a needle. However, investigations of changes in visual processing near the hands have essentially only examined effects associated with the power grasp hand posture. A one-size-fits-all approach to nearby-hand effects on vision ignores the possibility that the posture of the hands themselves—and the actions these postures afford—could potentially shape visual processing biases near the hands. Recent findings suggest that planning and preparing a particular action biases selection of action-congruent features in visual search (Wykowska et al., 2009). Similarly, viewing photographs of hands in particular postures can prime responses to objects that afford grasps of the same posture (Borghi et al., 2007). Such action-specific effects suggest that hand posture may also influence changes in visual processing near the hands.

As a first step in investigating the influence of changes in hand posture on nearby-hand vision effects, I asked participants to perform a visual task not only under the typical open palm posture that affords power grasps, but also under a complimentary pincer posture that affords precision grasps (see **Figure 1**). Depending on the activity intended, people typically adopt one of these two postures to grip nearby objects—flexing the fingers around an object to hold it against the palm in a power grasp or securing an object between the pads of the thumb and fingers in a precision grasp (Napier, 1956). Observers represent objects based on whether they more readily afford power or precision grasps (Tucker and Ellis, 2001, 2004), and viewing pictures of hands in these two different grasp postures automatically biases attention to grasp-congruent objects in a display (Fischer et al., 2008). People have extensive experience using both power and precision grasps and presumably associate each grasp posture with the specific class of actions it affords, making a comparison of these two postures a solid test case of the hypothesis that the affordances of hand postures modulate nearby-hand effects on vision.

To examine the influence of grasp posture on visual processing near the hands, I employed the classic attentional orienting paradigm (Posner et al., 1987) that Reed et al. (2006) used in their seminal paper on nearby-hand effects. In the original work, Reed et al. (2006) asked participants to detect the appearance of a visual target that could appear either to the right or left of a central fixation cross. In some conditions, participants placed either their left hand next to the left-side target location or their right hand next to the right-side target location with the open palm facing the target. The authors found that participants were faster to detect targets appearing near their hands than targets away from their hands, suggesting that attention is prioritized to the space near the hands (Reed et al., 2006). Additional experiments replicated and extended these findings, showing that facilitation occurs for targets appearing near the open palm of the hand—targets positioned with respect to the hand in a manner affording a power grasp—but not for targets near the back of the hand (Reed et al., 2010). The experiments presented here investigate this attentional prioritization effect, examining whether prioritization of space near the hands is dependent upon grasp posture. While I find evidence for attentional prioritization of the space near the hands when observers position their hands for a power grasp, when they instead position their hands for a pincer grasp, this prioritization effect disappears.

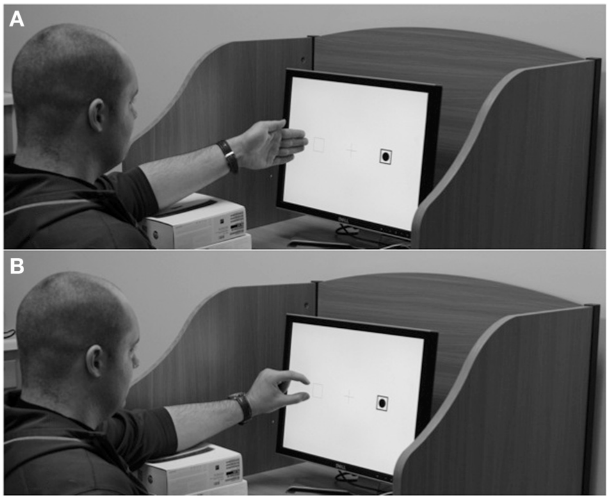

FIGURE 1 | Grasp postures in (A) the palm conditions of Experiments 1 and 3 and (B) the pinch conditions of Experiments 2 and 3.

EXPERIMENT 1

In order to investigate the influence of grasp posture on attentional prioritization of the space near the hands, it is prudent to first replicate the original finding that observers are faster to detect targets near a hand positioned on the screen in a relaxed power grasp posture—thumb side up, fingers held together in a single unit—than targets far from the hand. I compared participants' performance on the standard covert attention task under conditions in which they held their left or right hand on the display in this posture against conditions in which participants instead rested one of their hands in their laps.

METHODS

PARTICIPANTS

Twenty-five right-handed undergraduate volunteers from Vanderbilt University participated for course credit. The Vanderbilt University Institutional Review Board approved the experimental protocol and all participants provided informed consent.

STIMULI AND APPARATUS

Stimuli were presented on a color monitor set at a resolution of 1024 × 768 pixels and a refresh rate of 89 Hz. Participants sat approximately 55 cm from the monitor. All stimuli were black presented on a white background. The stimuli consisted of a fixation cross (3°), two empty squares (3°) that were 6° to the left and right of fixation, and a target dot (2.3°). Participants made responses with a standard keyboard.

PROCEDURE AND DESIGN

Participants performed an attentional orienting target detection task designed to match the conditions of the original Reed et al. (2006) study. Each trial began with the presentation of a central fixation cross flanked by an empty square to the left and an empty square to the right. After a random delay between 1500 and 3000 ms, the border of one of the two squares darkened, serving as a cue to the target location. On 70% of trials, this cue was valid and a solid target dot appeared in the cued square 200 ms later and remained on the display until participants indicated they had detected the target by pressing the "h" key on the keyboard. On 20% of trials, the cue was invalid and the target instead appeared in the opposite square and again remained on the display until participants made a detection response. The remaining 10% of trials served as catch trials in which no target dot appeared; on these trials, the cue display remained onscreen for 3000 ms before the next trial began.

Participants performed blocks of trials in four hand posture conditions. In the *left-rest* condition, participants responded with their right hand and rested the free left hand in their laps. In the *right-rest* condition, participants responded with their left hand and rested their right hand in their laps. In the *left-palm* condition, participants again responded with their right hand, but extended their left hand to rest against the display next to the left target position. Finally, in the *right-palm* condition, participants responded with the left hand and extended the right hand to rest against the display next to the right target position. For the palm conditions, participants held their hands with the fingers together, thumb side up, with their palms facing toward the center of the screen in the same relaxed position affording a power grasp employed in previous investigations (Reed et al., 2006, 2010). Before a block of trials in the palm conditions began, participants viewed a display with written instructions about hand placement, the target boxes and fixation cross, and three small filled dots (0.5°) arranged in a vertical line subtending 3.5° placed 1.5° to the side of one target box that served as a guide to help them position the hand in a consistent location on the display. These guide dots were removed before the first trial in a block began. Before each block of trials in the rest conditions, participants viewed a display showing written instructions about hand placement as well as the target boxes and fixation cross. In the palm conditions, participants rested their extended arm on a brace to minimize discomfort. Participants performed a short block of 20 practice trials in the left-rest condition before completing two blocks of 60 trials each in the four hand conditions for a total of 480 trials. Both trials within a block and hand conditions across blocks were presented in a randomized order.

RESULTS AND DISCUSSION

One participant made excessive response errors on catch trials (>50%) and was excluded from analyses. The remaining 24 participants incorrectly made a response on an average of 11.73% of catch trials; data for these trials were not analyzed. To eliminate anticipation and inattention errors, trials with a reaction time of less than 100 ms or greater than two standard deviations from a participant's mean reaction time were also excluded from the analyses. Mean reaction times were calculated to targets on the right and left side under each of the four hand conditions[1] and are displayed in **Figure 2**.

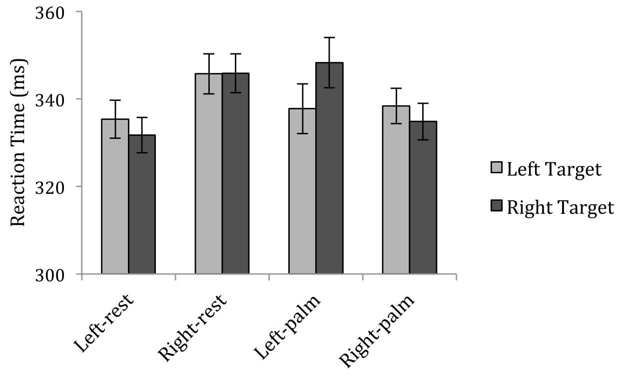

FIGURE 2 | Mean reaction times to detect targets in Experiment 1.

If participants prioritize the space near the hand as previous research suggests (Reed et al., 2006, 2010), then participants should be facilitated in detecting targets appearing on the same side as their hand in the palm conditions. A repeated measures analysis of variance with factors of Hand Posture (rest vs. palm), Response Hand (left vs. right) and Target Side (left vs. right) showed that participants tended to be faster making responses with their dominant hand than their non-dominant hand when in the rest conditions: Hand Posture × Response Hand interaction, $F_{(1,\ 23)} = 4.84$, $p = 0.038$. More importantly, participants were also relatively faster to detect targets appearing near a hand positioned in the palm posture that affords a power grasp than targets appearing away from a hand: Hand Posture × Response Hand × Target Side interaction, $F_{(1,\ 23)} = 4.07$, $p = 0.056$. To interpret this marginally significant 3-way interaction, separate ANOVAs with factors of response hand and target side were conducted for each hand posture. These analyses confirmed that the interaction between response hand and target side was significant in the palm conditions, $F_{(1,\ 23)} = 4.77$, $p = 0.039$ (left-palm condition: left targets = 338 ms vs. right targets = 348 ms; right-palm condition: left targets = 338 ms vs. right targets = 335 ms), but not the rest conditions, $F_{(1,23)} < 1$, *ns* (left-rest condition: left targets = 335 ms vs. right targets = 332 ms; right-rest condition: left targets = 346 ms vs. right targets = 346 ms). These *post-hoc* analyses also showed a main effect of response hand for the rest conditions, $F_{(1,\ 23)} = 7.75$, $p = 0.011$. No other main effect or interaction approached significance (all p-values > 0.1).

The results of Experiment 1 serve as an independent replication of the attentional prioritization effects previously documented by Reed and her colleagues (2006, 2010). When participants held their hand on the display in a posture that affords a power grasp, they were facilitated in detecting targets that appeared next to their open palm. However, the side on which a target appeared had no influence over reaction times when participants instead held their free hand in their laps. Having thus confirmed the reproducibility of the original attentional prioritization findings, in Experiment 2 I investigated whether observers also prioritize the space near their hands when they adopt a pincer grasp posture.

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[1] Previous investigations have found that cue validity does not influence attentional prioritization of space near the hand (Reed et al., 2006, 2010). I have chosen to collapse the data across valid and invalid trials to simplify presentation of results. The pattern of data was similar across both valid and invalid trials in all experiments.

EXPERIMENT 2

Recent studies examining visual processing near the hands seem to suggest that, as long as visual stimuli appear within the hands' functional space, nearby-hand effects should occur. Yet the hands can serve multiple functions, and observers' experiences may create biases toward visual information that is relevant for different types of actions (e.g., Wykowska et al., 2009). To investigate the possibility that hand posture influences visual processing biases, in Experiment 2, I asked participants to perform the same covert orienting task while holding one hand next to a target location on the display, but in this case, they positioned their hand in a pincer posture in which the thumb and forefinger rested near the target location, affording a precision grasp. As in the previous experiment, this posture places targets near the hand within its functional grasping space. However, the type of grasp that observers were positioned to perform is quite different, and this is a difference to which the visual system is attuned (Tucker and Ellis, 2001, 2004; Fischer et al., 2008). In Experiment 2 participants were essentially at the ready for a precise action instead of a power action. If proximity to the functional space of a hand alone facilitates target detection, then participants in Experiment 2 should show the same effect of attentional prioritization near the hands as did participants in Experiment 1. However, if grasp posture has an influence on visual processing near the hands, then the pattern of data for Experiment 2 may differ from the near-hand facilitation effect I found in the first experiment.

METHODS

PARTICIPANTS

Twenty-four right-handed undergraduate volunteers from North Dakota State University participated for course credit. The North Dakota State University Institutional Review Board approved the experimental protocol and all participants provided informed consent.

STIMULI, APPARATUS, PROCEDURE, AND DESIGN

Stimuli identical to those used in Experiment 1 were presented on a color monitor set at a resolution of 1024 × 768 pixels and a refresh rate of 75 Hz. Participants again sat approximately 55 cm from the monitor and performed the target detection task from Experiment 1. They performed blocks of trials in four hand posture conditions, two of which were replications of the rest conditions in Experiment 1, with identical instruction screens at the beginning of each block. In addition, participants performed the attentional orienting task under two new hand posture conditions in which they rested a hand against the display in a pincer grasp posture. In the *left-pinch* condition, participants responded with their right hand on the keyboard and extended their left hand to rest against the display next to the left target position. In the *right-pinch* condition, participants responded with the left hand and rested the right hand against the display next to the right target position. For the pinch conditions, instead of extending their hands with the fingers together, participants held their thumb and forefinger next to an empty square, positioned in a manner affording precision grasps (see **Figure 1B**). Before a block of trials in the pinch condition began, participants viewed a display with written instructions about hand placement, the target boxes and fixation cross, and two filled dots arranged vertically—one slightly above the target box, the other slightly below, again subtending 3.5°—that served as a guide indicating where the thumb and forefinger should rest during the upcoming trials. In these conditions, participants rested their extended arm on a brace to minimize discomfort. Participants performed a short block of 20 practice trials in the left-rest condition before completing two blocks of 60 trials each in the four hand conditions—480 trials total—in a randomized order.

RESULTS AND DISCUSSION

Participants incorrectly made a response on an average of 17.97% of catch trials for which data were not analyzed. Anticipation and inattention errors were excluded from analyses using the same criteria as in Experiment 1. **Figure 3** displays mean reaction times across conditions for Experiment 2.

If observers prioritize the space near the hands—regardless of the hands' posture—then participants should again be faster to detect targets appearing near the hand than away from the hand in the pinch conditions. A repeated measures analysis of variance with factors of Hand Posture (rest vs. pinch), Response Hand (left vs. right) and Target Side (left vs. right) showed only that participants tended to respond more quickly in the pinch conditions than the rest conditions: main effect of Hand Posture, $F_{(1,\ 23)} = 5.30$, $p = 0.031$, possibly indicating greater overall arousal when a hand was held on the display in a precision posture[2] (left-pinch condition: left targets = 374 ms vs. right targets = 368 ms; right-pinch condition: left targets = 378 ms vs. right targets = 369 ms; left-rest condition: left targets = 383 ms vs. right targets = 388 ms; right-rest condition: left targets = 394 ms vs. right targets = 412 ms). No other main effect or interaction approached significance (all p-values > 0.1).

Although participants in Experiment 2 performed the same target detection task as participants in Experiment 1, unlike

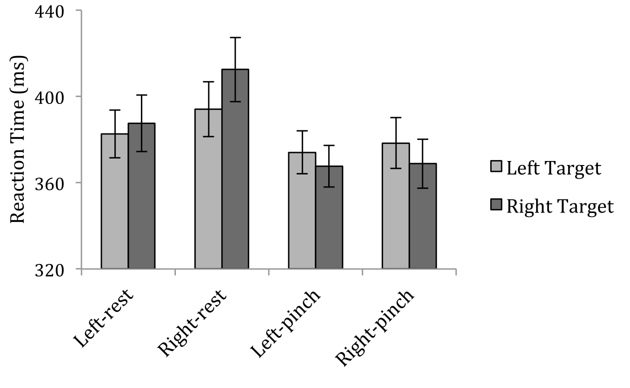

FIGURE 3 | Mean reaction times to detect targets in Experiment 2.

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[2] While fMRI evidence shows that executing both power and precision grasps activates primary motor cortex, precision grasps are also associated with more widespread bilateral BOLD activity in premotor and parietal areas, suggesting that a precision grasp is more demanding in terms of neural control (Ehrsson et al., 2000). The pinch hand posture may therefore be more arousing compared to a baseline rest condition than the power hand posture.

participants in the first experiment, these observers were no faster to detect targets appearing near their hands than targets appearing away from their hands. The pattern of performance in the pinch condition was similar to the pattern of performance in the rest condition, suggesting that, at least from a target location standpoint, there was no difference between performing the task while a hand was on the display than when it rested in a participant's lap. A difference in hand proximity across experiments cannot explain this pattern of results: participants in Experiment 2 held their hands just as close to the target locations as participants in Experiment 1. Likewise, the lack of attentional prioritization of the space near the hands cannot be due to the fact that targets appeared outside of functional hand space: as in Experiment 1, near-hand targets in Experiment 2 appeared within the hands' grasping space. Instead, the different pattern of results across these two experiments must be a function of the different grasp postures participants adopted while performing the task. Holding the hand in an open palm posture that affords a power grasp creates an attentional bias to the space near the hand, but observers who held their hands in a pincer posture that affords a precision grasp were no more likely to attend to locations near their hand than locations away from their hand.

EXPERIMENT 3

Although the pattern of results across the first two experiments suggests that attentional prioritization occurs for the space near hands positioned for a power, but not a precision grasp, it is difficult to firmly conclude that grasp posture influences the allocation of attention near the hands without directly comparing the two grasps in a single study. In other words, the fact that participants showed significant facilitation in detecting targets near the hands in Experiment 1, but no significant facilitation in Experiment 2 does not necessarily imply the difference between performance under power grasp and precision grasp postures is itself significant. I address this issue in Experiment 3 by asking a single group of participants to perform the attentional orienting task under both the palm conditions of Experiment 1 and the pinch conditions of Experiment 2. If grasp posture modulates attentional prioritization near the hands, then participants in this experiment should be facilitated in detecting targets near the hand in the palm conditions, but not the pinch conditions.

METHODS

PARTICIPANTS

Twenty-nine right-handed undergraduate volunteers from North Dakota State University participated for course credit. The North Dakota State University Institutional Review Board approved the experimental protocol and all participants provided informed consent.

STIMULI, APPARATUS, PROCEDURE, AND DESIGN

Experiment 3 was a replication of the previous two experiments combining the palm and pinch conditions of Experiments 1 and 2. Following a short block of 20 practice trials in which participants responded with the right hand and held their left hand in their laps, participants performed two blocks of 60 trials each of the left-palm, right-palm, left-pinch, and right-pinch conditions—a total of 480 trials—in a randomized order.

RESULTS AND DISCUSSION

Five participants made excessive response errors on catch trials (>50%) and were excluded from analyses. The remaining 24 participants incorrectly made a response on an average of 19.02% of catch trials for which data were not analyzed. Anticipation and inattention errors were excluded from analyses using the same criteria as in the previous experiments. **Figure 4** displays mean reaction times across conditions for Experiment 3.

To look for supporting evidence that grasp posture modulates attentional prioritization of the space near the hands, I conducted a repeated measures analysis of variance with factors of Hand Posture (palm vs. pinch), Response Hand (left vs. right) and Target Side (left vs. right). A significant interaction between hand posture, response hand, and target side, $F_{(1,\ 23)} = 4.71$, $p = 0.041$ mediated main effects of hand posture, $F_{(1,\ 23)} = 8.54$, $p = 0.008$, and target side, $F_{(1,\ 23)} = 6.89$, $p = 0.015$, and interactions between posture and response hand, $F_{(1,\ 23)} = 6.84$, $p = 0.016$, and response hand and target side, $F_{(1,\ 23)} = 6.75$, $p = 0.016$. An examination of **Figure 4** indicates that a facilitation of responses near the left hand in the palm condition coupled with a lack of difference between responses to targets near vs. away from the hands in the pinch conditions drove the significant three-way interaction. Separate *post-hoc* analyses for each hand posture confirm this impression: while there was a significant main effect of target side, $F_{(1,\ 23)} = 12.15$, $p = 0.002$ mediated by a significant interaction between response hand and target side, $F_{(1,\ 23)} = 8.84$, $p = 0.015$ in the palm conditions (left-palm condition: left targets = 336 ms vs. right targets = 354 ms; right-palm condition: left targets = 352 ms vs. right targets = 352 ms), only the main effect of response hand was significant in the pinch conditions, $F_{(1,\ 23)} = 7.00$, $p = 0.014$, with participants being somewhat slower to respond with their dominant right hand when their left hand was on the display (left-pinch condition: left targets = 365 ms vs. right targets = 370 ms; right-pinch condition: left targets = 354 ms vs. right targets = 357 ms). No other main effect or interaction approached significance (all p-values > 0.1).

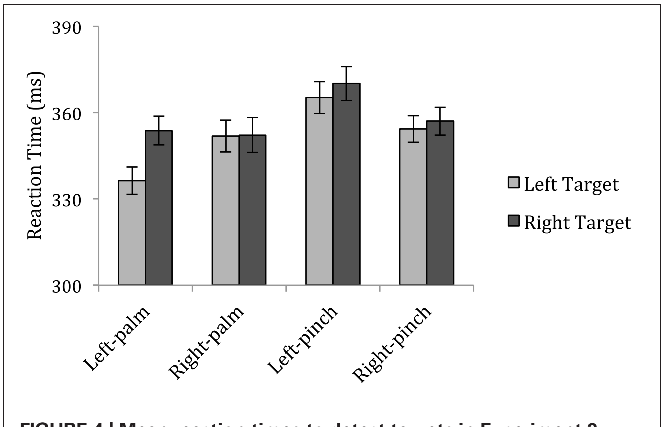

FIGURE 4 | Mean reaction times to detect targets in Experiment 3.

The results of Experiment 3 provide a replication of the key findings of the first two experiments: participants were once again faster to respond to targets appearing near the hand in the palm conditions, but did not show the same facilitation when targets appeared near the hand in the pinch conditions. Again, although the targets appeared in the hands' grasping space in both the palm and pinch conditions and participants held their hands equally close to the target locations under both postures, they only prioritized targets near their hands when the hands were positioned to afford a power grasp. Importantly, the interaction between hand posture, response hand, and target side was significant, providing a direct contrast between nearby-hand effects under a power vs. precision grasp posture.

GENERAL DISCUSSION

Nearby-hand effects on vision may reflect adaptations that allow observers to determine appropriate responses to nearby objects by processing these candidates for action differently than more distant stimuli (Graziano and Cooke, 2006; Abrams et al., 2008; Brockmole et al., 2013). The majority of work investigating these effects has focused on how the presence of the hands, in general, influences processing. The results of the current study suggest that the presence of the hands will not always necessitate the same specific alterations in processing, but instead that biases in visual processing near the hands can change when observers position their hands to afford different types of actions.

Across three experiments, I found evidence that attentional prioritization near the hands relies upon the hands' posture. While participants in Experiments 1 and 3 demonstrated a clear attentional bias toward locations near their hands, detecting targets more quickly when they appeared within power grasping space[3], participants in Experiments 2 and 3 who instead held their hands in a pincer grasp posture did not favor targets appearing on one side of the display over another. In other words, observers prioritized their attention to the hands' functional grasping space, but only when the hands were at the ready for a power, and not a precision, grasp. These results suggest that changes in visual processing near the hands rely not only on the relationship between the hands' location and the relevant visual information (i.e., Reed et al., 2010; Adam et al., 2012), but also the potential actions that the hands' positioning affords.

Why would observers be biased to attend to the space near their hands when in a power grasp posture, but not when in a precision grasp posture? If adaptations for effective action production drive nearby-hand effects, then the influence the hands exert over visual processing should be modulated by the context between the nature of the processing task and stimuli and the hands' affordances for action. Although the data suggest that participants were no more biased to attend to one side of a display when their hands were in the pinch posture than they were when their hands were in their laps, this does not necessarily imply that precision grasping hands will never alter visual processing. Bimodal neurons show selectivity based on observed object size and power vs. precision grasps (e.g., Fadiga et al., 2000), raising the possibility that representations related to different hand postures may lead to different visual biases. The precision grasp posture may have been ill suited to meet the demands of the attentional orienting task, but perhaps a more detail-oriented visual task could be more compatible with this posture. The visual biases that aid a rugby player in catching a pass may differ substantially from those that help a tailor thread a needle.

A recent finding in the literature on nearby-hand effects may speak to this possibility. Gozli et al. (2012) found that observers were better at a temporal gap detection task when they grasped the display between both hands than when they kept their hands away from the display, but were better at a spatial gap detection task when their hands were far from the display. The authors suggest that placing the hands near an object biases visual information processing toward increased contributions from the high temporal, low spatial resolution magnocellular pathway (Pokorny and Smith, 1997; Maunsell et al., 1999), while keeping the hands away from an object biases contributions from the high spatial, low temporal resolution parvocellular visual pathway (Derrington and Lennie, 1984; Pokorny and Smith, 1997). Gozli et al. (2012) argue these results are consistent with a framework in which observers prioritize action when processing objects near the hands, but prioritize perception when processing objects far from the hands. Data from the palm conditions of the current study are in line with this theory: the power grasping posture facilitated a target detection task requiring rapid responses to large changes in luminance to which the magnocellular pathway is sensitive. However, although the precision grasp posture does afford an action, instead of creating a bias toward the action-oriented magnocellular pathway, it may have introduced bias toward the more detail-oriented parvocellular pathway. The precision grasp posture affords actions that bring nearby objects into contact with the pads of the thumb and forefingers, areas of the hand with high tactile spatial acuity that aid in delicate work, while the power grasp posture affords actions that bring objects into contact with the base of the fingers and palm, areas of the hand with lower tactile sensitivity that enable faster and more forceful work (Johansson and Vallbo, 1979; Craig, 1999; Craig and Lyle, 2001). An observer who is prepared to perform a power grasp is ready to make a quick action, as in the case of a rugby player catching a pass. On the other hand, an observer who is at the ready to interact with an object using a precision grasp, such as a tailor threading a needle, may benefit from a more fine-grained analysis of the object's visual properties. The findings of the current study are consistent with the theory that power grasps bias processing toward contributions from the magnocellular pathway. Future work will be necessary to explore the notion that precision grasps may enhance parvocellular contributions.

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[3] Participants in these experiments were specifically facilitated in detecting targets near the left palm. Although some previous research suggests that in identification paradigms, right-handed participants show stronger nearby-hand effects for stimuli appearing near their dominant hand (Lloyd et al., 2010; Tseng and Bridgeman, 2011), the facilitation in detecting targets appearing near the left hand in the current study mirrors the findings of Reed et al. (2006) in both direction and magnitude. These differences in lateralization across studies have yet to be thoroughly investigated, but may be driven by differences in experimental paradigms or task demands (Tseng et al., 2012).

The results of the current study provide the first evidence that changes in visual processing near the hands may rely on the hands' grasping posture. As work investigating nearby-hand effects on vision moves forward, it is important to consider not only how the hands' presence can alter processing, but also how the hands' potential for actions may modulate these effects. An examination of the influence of hand posture on processing biases may ultimately point the way toward enhanced understanding of the underlying mechanisms of vision near the hands.

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Determinants of attentional modulation near the hands

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A series of visual search experiments conducted by Abrams et al. (2008) indicates that disengagement of visual attention is slowed when the array of objects that are to be searched are close to the hands (hands on the monitor) than if they are not close to the hands (hands in the lap). These experiments establish the impact one's hands can have on visual attentional processing. In the current paper we more closely examine these two hand postures with the goal of pinpointing which characteristics are crucial for the observed differences in attentional processing. Specifically, in a set of 4 experiments we investigated additional hand postures and additional modes of response to address this goal. We replicated the original Abrams et al. (2008) effect when only the two original postures were used; however, surprisingly, the effect was extinguished with the new range of postures and response modes, and this extinction persisted across different populations (German and English students), and different experimental hardware. Furthermore, analyses indicated that it is unlikely that the extinction of the effect was caused by increased practice due to additional blocks of trials or by an increased probability that participants were able to guess the purpose of the experiment. As such our results suggest that in addition to the nature of the postures of the hand, the number of postures is a further important factor that influences the impact the hands have on visual processing.

Keywords: embodiement, hand posture, visual search, attentional disengagement, situational determinants

INTRODUCTION

In certain situations humans show an inclination to hold in their hands the target of visual perception. Regarding object perception, for example, the request "May I take a look at this?" often implicitly contains the request to be allowed to actually hold the object in one's own hands. Similarly, in reading, some people prefer to read with the text held in their hands rather than read on the computer screen, although the screen may actually provide better (perceptual) access to the text (e.g., due to adjustable size, contrast, and brightness or due to text processing tools such as full text search).

What are the reasons for such an inclination to hold in one's hands the target of visual perception? A set of recent studies suggests that one reason may be that the presence of the hands influences perceptual processes: The hands being closer to task-relevant visual stimuli modulates (a) the perceived size of objects (Vishton et al., 2007; Linkenauger et al., 2010), (b) the figure-ground assignment in the viewed stimuli (Cosman and Vecera, 2010), (c) the attentional prioritization of space (Reed et al., 2006, 2010; Davoli and Brockmole, 2012), and (d) the shifting of attention (Abrams et al., 2008; Pollux and Bourke, 2008; Davoli et al., 2012).

Take, for instance, the shifting of attention effect observed by Abrams et al. (2008) in a number of visual search experiments. In each of these experiments participants had to search for one of two target letters and press one of two corresponding response buttons once they found the target letter. On each trial 3 or 7 distracter letters were presented together with the target letter. Across blocks of search trials the location of participants' hands was varied such that during half of the blocks the hands were in the participant's lap (**Figure 1A**) and during the other half of the blocks, the hands were on the monitor (**Figure 1B**). It is common to observe a *set size effect* in visual search, that is, an increase of the time required to correctly respond to the present target with an increase of the number of distracters presented concurrently with the target. In line with this, Abrams et al. (2008) found reliably higher response times for search when 7 distracters were shown than when 3 distracters were shown. Furthermore, this set size effect (e.g., the slope of the response time function from 3 to 7 distractors) was significantly steeper when the hands were on the monitor than when they were in the lap (e.g., steeper slope for green line than red line in **Figure 1C**). Based on two additional experiments examining inhibition of return and attentional blink for the two hand postures, Abrams et al. (2008) concluded that the difference between the two hand postures in visual search was due to a modulation of attentional disengagement: When the hands are on the monitor it is harder to disengage attention from a currently attended distracter to continue search for the target. This in turn gives rise to a more pronounced set size effect for the screen posture than for the lap posture.

In combination with the other studies mentioned above, the work of Abrams et al. (2008) suggests that visual processing near the hands is characterized by enhanced perception, facilitated attentional engagement, slowed attentional disengagement, and increased focus on visual detail (Brockmole et al., 2013). These modulations of visual processing are often assumed to be rooted in the involvement of bimodal visuo-tactile neuron populations

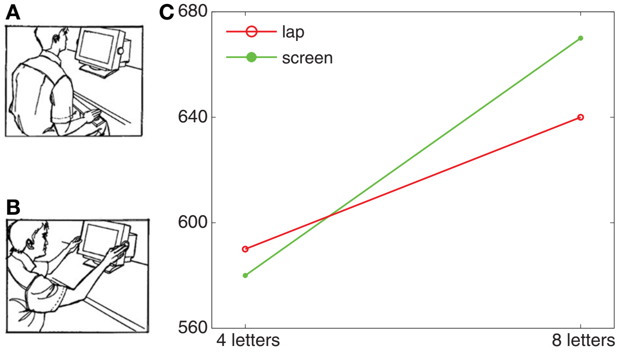


FIGURE 1 | Lap posture (A) and screen posture (B) as employed by Abrams et al. (2008) and an exemplary pattern of response time results (C). Parts **(A)** and **(B)** reproduced from Figure 1 of Abrams et al. (2008).

in the parietal and premotor cortices (Graziano and Gross, 1993; Tseng et al., 2012).

In the current paper, we more closely examine the attentional disengagement effect of Abrams et al. (2008), seeking to identify its situational determinants. We consider the following possibilities that emerge out of a comparison of differences across the screen and lap postures: *proximity*: whether the hands are close or not close to the task-relevant stimuli; *spanning*: whether the hands "embrace" the stimuli, that is, to what extent the stimuli are between the hands; *palms*: whether the palms of the hands face toward or away from the stimuli; and *response direction*: whether the response given by the hand is a response toward the visual stimuli or away from the stimuli. Previous research has suggested that the determinants proximity (Cosman and Vecera, 2010; Adam et al., 2012), spanning (Tseng and Bridgeman, 2011), and palms (Reed et al., 2010; see also Brown et al., 2009) have an influence on attentional modulation, particularly engagement and enhanced perception. We ask here whether these factors also influence attentional disengagement as reflected within the Abrams et al. paradigm. In previous work within this paradigm, the different determinants were either confounded [e.g., proximity, spanning, and palms in Abrams et al. (2008)] or not manipulated [e.g., spanning and palms in Pollux and Bourke (2008)]. We considered response direction as an additional potential situational determinant, because the ease with which hands may act on a stimulus is directly related to whether one responds toward or away from the stimulus, while one experiment of Abrams et al. (2008) found the attentional disengagement effect also when participants responded by foot (i.e., without the hands responding toward the stimulus).

These four situational determinants were investigated in the current experiments employing the same task as the experiments in Abrams et al. (2008). In Experiment 1, the hand postures lap and screen (**Figures 1A,B**, respectively), employed by Abrams et al. (2008) were complemented by new hand postures such that the postures differed in the extent to which they instantiated the determinants. In Experiment 1 we added two postures we called *pray* posture and *post* posture to yield the four postures shown in **Figure 2**. In the screen posture, the hands were close to the stimuli, spanned the stimuli, and the palms of the hands were facing the stimuli (i.e., instantiated proximity and spanning and palms). In the post posture, the hands spanned the monitor and were close to the screen (i.e., instantiated spanning and proximity) but the palms were not facing the stimuli. In the pray condition, the hands did not span the monitor and the palms were not facing the stimuli, but the hands were close to the screen (instantiating proximity). Finally, in the lap posture, the hands were far from the screen, did not span the monitor, and the palms did not face the stimuli (i.e., instantiated none of the factors). Accordingly, comparing the set size effects as reflected in the slopes across the different postures allowed us to examine the differential impact of the various determinants on attentional disengagement. If, for example, the set size effect was larger (i.e., a steeper slope) in the pray posture than in the lap posture, this would provide support for the idea that proximity alone contributes to a slowing of attentional disengagement. If the set size effect was larger in the screen posture than in the post posture, this would indicate that the palm determinant contributes to the slowing of disengagement in addition to the determinants proximity and spanning.

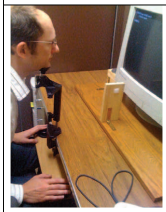
A lap	determinants	**B** pray	determinants
	none		proximity
C post	determinants	**D** screen	determinants
	proximity, spanning		proximity, spanning, palms

FIGURE 2 | Hand postures used in Experiment 1, labels for the hand postures, and determinants instantiated by the posture: (A) lap posture, **(B)** pray posture, **(C)** post posture, and **(D)** screen posture.

As shown in **Figure 3**, in Experiments 2–4 we examined the original screen and lap postures, and also a *board* posture which only instantiated proximity, and a *release* posture which was identical to the screen posture, but in which participants responded by releasing the appropriate response button, that is, the release posture instantiated the same determinants as the screen posture, but additionally manipulated the response direction determinant.

OVERVIEW OF EXPERIMENTS

Experiments 1–4 were all extended and modified versions of the visual search experiments of Abrams et al. (2008). The common methodology was as follows. On each trial, participants performed a visual search task to find a target letter among a

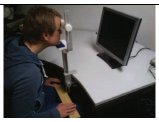
A board	**determinants**	**B lap**	**determinants**
	proximity		none
C release		**D screen**	
	proximity, spanning, palms, response direction		proximity, spanning, palms

FIGURE 3 | Hand postures used in the Experiments 2–4, labels for the hand postures, and determinants instantiated by the posture: (A) board posture, **(B)** lap posture, **(C)** release posture, and **(D)** screen posture.

set of letters simultaneously displayed in random locations on the screen. The target could be one of two letters, and participants responded based on the identity of the letter, pressing one response button for one letter and the other response button for the other letter. Each visual search screen was comprised of either 4 or 8 letters, with one of these letters being a target and the other letters being distracters. As soon as participants discovered the target, they were asked to press the corresponding response button. The buttons were configured in different positions across search trials, as described further below. All experiments included the two postures originally employed in Experiment 1 of Abrams et al. (2008), that is, the *lap* posture (**Figure 1A**) and the *screen* posture (**Figure 1B**). As in Abrams et al. (2008) the response time difference between small (4 letters) and large (8 letters) search sets (e.g., the slope, see **Figure 1C**) was used as an index of the set size effect, and the assumption was that stronger set size effects indicate slower attentional disengagement.

Our experiments extended the original experiments by augmenting the lap and the screen postures with additional postures. In Experiment 1 we added the pray and post postures as shown in **Figure 2** and described earlier. Surprisingly, Experiment 1 failed to replicate the original finding of Abrams et al. (2008), with no significant difference in the set size effects between the lap and screen postures. Therefore, in Experiments 2–4 we set out to discover why the effect became extinguished. In doing so, we employed a physical set up (see **Figure 3**) that was more similar to that of Abrams et al. (2008). In Experiment 2, we included only the lap (**Figure 3B**) and screen postures (**Figure 3D**) so as to directly replicate Abrams et al. (2008). Since replication was successful in Experiment 2, Experiment 3 was designed to investigate whether the replication failure in Experiment 1 was due to the physical setup or the addition of extra postures. Accordingly, Experiment 3 added the board (**Figure 3A**) and release (**Figure 3C**) postures to the lap and screen postures. Interestingly, Experiment 3 again failed to replicate the originally found difference between the lap and screen postures. This leads us to believe that the extinction of the original effect was likely caused by the addition of extra postures. In Experiment 4 we asked how sensitive the original effect is to the addition of postures by adding only a single extra posture, the release posture, to the lap and screen postures. The fact that Experiment 4 failed to replicate the original effect provided additional support to the idea that the extinction of the effect is caused by adding extra postures to the original setup.

EXPERIMENT 1

In Experiment 1, the four postures employed were lap, pray, post, and screen. As indicated in **Figure 2**, these four postures differed in the extent to which the determinants proximity, spanning, and palms were instantiated when participants placed their hands on the buttons to respond during the visual search task. Accordingly, if proximity contributed to the slowing of attentional disengagement effected by the hands, one would expect a difference in the set size effects between the lap and the pray posture. If spanning had a substantial impact on the slowing of attentional disengagement, this should show up as a difference in the set size effects between the pray and the post posture, and if palms influenced attentional disengagement, one should observe a difference in the set size effects between the post and the screen posture.

METHODS

Participants

Sixty-two University of Notre Dame undergraduates participated in Experiment 1. They were compensated by partial credit for an undergraduate psychology course. All participants in this and subsequent experiments gave informed consent.

Materials and apparatus

Participants sat facing a 20″ CRT monitor with their chins in a chinrest. The chair and chinrest were adjusted for each participant such that their eyes were vertically and horizontally aligned with the center of the monitor. Following Abrams et al. (2008), each visual search set contained one target letter and 3 or 7 distracter letters. The target letter was either an "S" or an "H" and all letters were 3° high and 1.5° wide. Search sets were presented in a display area that measured 33° of visual angle wide and 21° of visual angle high, centered on the monitor's center. The location of the letters was determined randomly, subject to the constraint that any two letters were at least 0.75° apart. In contrast to Abrams et al. (2008), we employed "R" and "T" (instead of "U" and "E") as distracter letters to avoid the possibility that the randomly placed target and distracters might spell anything meaningful. Each distracter was randomly determined to be either an "R" or a "T." Response buttons were 6 cm in diameter and were attached so as to configure different postures across trials, as described above. The buttons were connected to the computer through a modified keyboard such that pressing the buttons produced the characters "/" and "z," respectively.

The distance between the two hands was 35, 5, 60, and 53 cm in the lap, pray, post, and screen postures, respectively. The distance of the hands to the monitor was 50, 10, and 3.5 cm in the lap, pray, and post postures, respectively. The distance between the viewer and the hands was 30 cm in the pray posture and 40 cm in the post and screen postures.

Procedure

At the start of each trial a fixation cross (1.5° × 1.5°) was shown at the center of the display area. After 500 ms the fixation cross was replaced with the search set. Participants were instructed to identify which of the two target letters was present, and to indicate its identity by pressing the corresponding response button. The mapping of target letters to response buttons was counterbalanced across subjects. Once a button was pressed, the participant received feedback when the response was faster than 100 ms ("Too fast!"), slower than 1500 ms ("Too slow!"), and/or the wrong button was pressed ("Wrong key pressed!"). The inter-trial-interval was 2000 ms.

Overall, each participant performed 256 trials that were presented in a set of 4 blocks of 64 trials each. For each block the hands were in a different posture, with the order of postures counterbalanced across subjects. Of the 64 trials in each block, there were 16 replications of all possible target letter-set size (S-setsize 4; H-setsize 4; S-setsize 8; H-setsize 8) combinations.

RESULTS

A 0.05 level of significance was adopted for conventional statistical analyses in this and all following experiments. The conventional analysis was complemented by a Bayesian analysis as described in Masson (2011; see also Wagenmakers, 2007). This analysis provided the probability $P_{\text{BIC}}(H_0|D)$ that the null hypothesis, H_0, was true given the available set of data D. The probability of the alternative hypothesis H_1 can be computed as $P_{\text{BIC}}(H_1|D) = 1 - P_{\text{BIC}}(H_0|D)$. To indicate the support the experimental results lend to H_0 and H_1, respectively, the probabilities $P_{\text{BIC}}(H_0|D)$ are reported in addition to the results of the conventional analysis. Since accuracies were often very close to 100%, they were arcsine-transformed before statistical analyses.

Response times

Trials in which participants answered incorrectly were excluded from response time analyses. Furthermore, standard deviations and means were computed for each individual and condition and response times outside a $2.5 * SD$ range from the mean were excluded from analyses[1]. Overall 7% of all trials were excluded from analyses.

Figure 4A and **Table 1** show the mean response times and the set size effects, respectively, for the four postures. A 4 (posture) × 2 (set size) analysis of variance revealed that search was faster in small ($M = 568$ ms) than in large ($M = 656$ ms) sets [$F_{(1,\,61)} = 332.2$, $p < 0.001$; $P_{\text{BIC}}(H_0|D) < 10^{-25}$]. Posture had no clear effect on search speed [Ms = 613, 612, 614, and 609 ms for lap, post, pray, and screen postures, respectively; $F < 1$; $P_{\text{BIC}}(H_0|D) = 0.92$] nor on set size effects [mean response time differences between set size 8 and set size 4 were 87, 90, 80, and 95 ms for lap, post, pray, and screen, respectively; $F < 1$, $P_{\text{BIC}}(H_0|D) = 0.79$]. In particular there was no significant difference in set size effects between lap and screen postures [$F < 1$, $P_{\text{BIC}}(H_0|D) = 0.85$].

Practice effects

To our surprise, Experiment 1 did not replicate the difference between set size effects in the lap and screen postures originally reported by Abrams et al. (2008). One potential cause for the failure to replicate are practice effects that might have been brought about by including two additional postures. Assuming that the participants' skill in performing the visual search task increases with the duration of performing the search task, adding extra postures might have given rise to more skilled visual search performance. If more skilled performance is not subject to the same attentional modulation as less skilled performance, an elimination of the attentional disengagement effect found by Abrams et al. (2008) could have resulted. Accordingly, adding extra postures may have lead to practice effects that eliminate differences in attentional disengagement between postures.

To assess the existence of practice effects and their potential impact on attentional disengagement, we conducted a set of extra analyses for this and all following experiments. The first set of analyses collapse across the specific postures and consider search performance by block instead. Replacing the factor posture by the factor block allowed examination of how search speed and set size effects depend on the block number, that is, on how much practice participants had already gained in the visual search task. The second set of analyses compares two groups of participants[2]. Group 1 consists of participants that experienced the lap and screen postures in the first two blocks; group 2 consists of participants that experienced the lap and screen postures in the last two blocks.

A 4 (block) × 2 (set size) analysis of variance revealed that search got faster with increasing practice [651, 613, 597, and 587 ms for blocks 1, 2, 3, and 4, respectively; $F_{(3,\,183)} = 21.6441$, $p < 0.001$, $P_{\text{BIC}}(H_0|D) < 7.5 * 10^{-12}$]. Furthermore, a significant block × set size interaction indicated that the set size effect decreased with practice [103, 89, 79, 77 ms for blocks 1, 2, 3, and 4, respectively; $F_{(3,\,183)} = 3.4754$, $p < 0.05$, $P_{\text{BIC}}(H_0|D) = 0.073$]. More specifically, the overall interaction was largely driven by significant differences in set size effects between block 1 and block 3 [$F_{(1,\,61)} = 6.1683$, $p < 0.05$, $P_{\text{BIC}}(H_0|D) = 0.28$] as well as block 1 and block 4 [$F_{(1,\,61)} = 7.9136$, $p < 0.01$, $P_{\text{BIC}}(H_0|D) = 0.15$].

A 2 (posture) × 2 (set size) × 2 (presentation time) analysis of variance with the first two factors within subjects and the third factor between subjects also indicated that search got faster with increasing practice [652 ms and 597 ms for participants experiencing lap and screen in the first and last blocks, respectively; $F_{(1,\,20)} = 4.778$, $p < 0.05$, $P_{\text{BIC}}(H_0|D) = 0.308$]. However, the lack of any significant interaction involving presentation time suggests that practice had no clear effect on the differences in the magnitude of the set size effect between the lap and screen postures.

Nevertheless, the first type of practice analysis indicates an impact of practice on the magnitude of the set size effect and, accordingly, raises the possibility that the failure to replicate

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[1] To check to what extent our results depend on the exclusion criterion we also analyzed response times after only excluding times that were faster than 100 ms or slower than 1500 ms. These analyses yielded the same pattern of significances as the analyses reported in the paper.

[2] We thank one of the reviewers for suggesting this additional analysis.

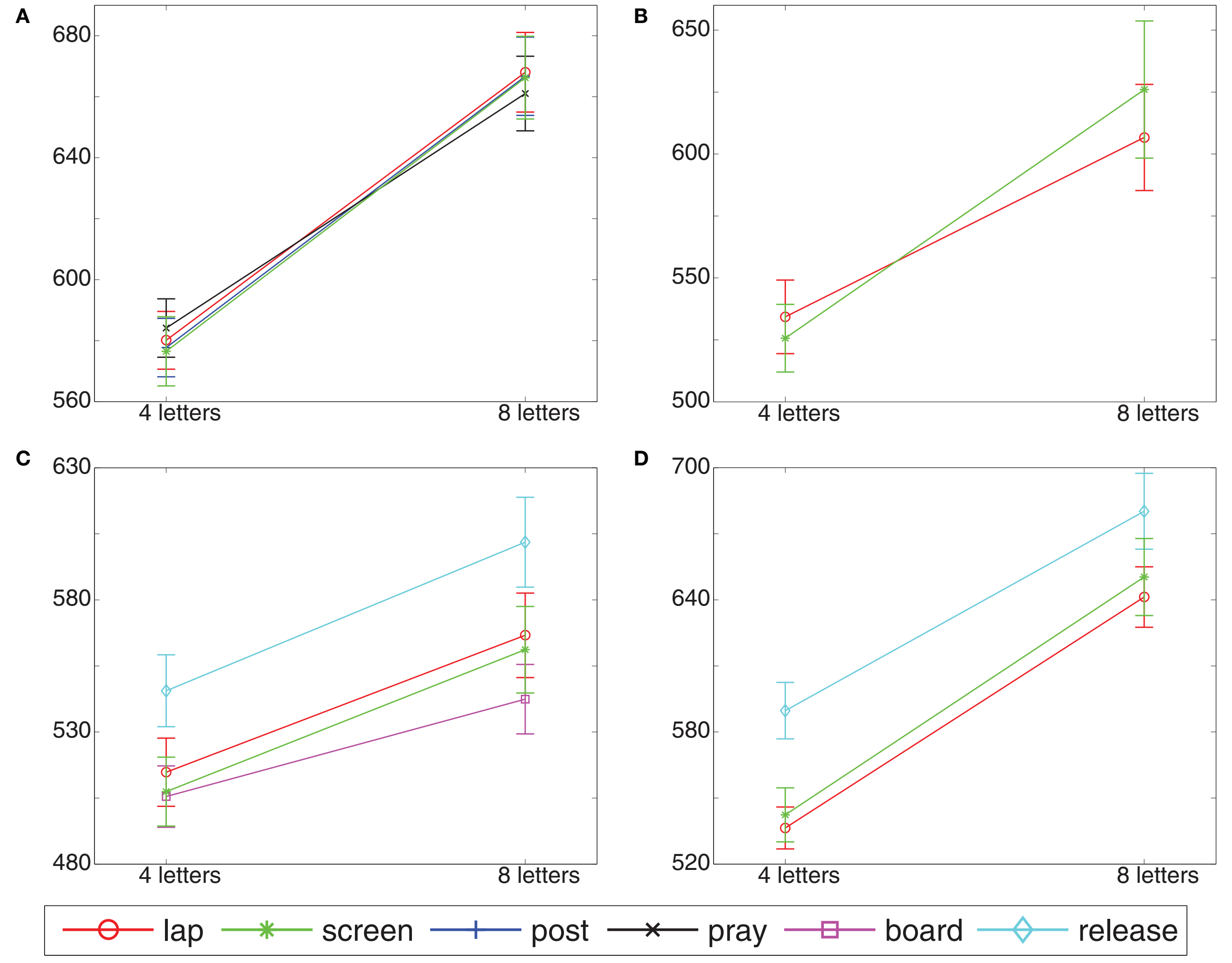

FIGURE 4 | Response time results for Experiment 1 (A), Experiment 2 (B), Experiment 3 (C), and Experiment 4 (D).

the original difference in set size effects between lap and screen postures is due to practice effects. To further investigate this possibility, we re-analyzed the response times considering only data from the lap and screen postures of those participants that experienced these postures in the first two blocks ($N = 12$). The resulting 2 (posture) × 2 (set size) analysis of variance exhibited no clear indication for differences in set size effects for lap (94 ms) and screen (104 ms) postures [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.76$]. Consequently, although practice had an impact on the magnitude of set size effects, our results did not find any evidence that these practice effects were responsible for not replicating the original finding of Abrams et al. (2008).

Accuracies

Table 2 shows the mean accuracies for the four postures. Accuracies were generally high, ranging from 82% to 100% with a mean accuracy of 96%. A 4 (posture) × 2 (set size) analysis of variance revealed no effect of posture [$F_{(3,\ 183)} = 1.8257$, $p > 0.14$; $P_{\mathrm{BIC}}(H_0|D) = 0.47$] and no interaction [$F_{(3,\ 183)} = 1.1161, p > 0.34$; $P_{\mathrm{BIC}}(H_0|D) = 0.72$]. The main effect of set size was significant [$F_{(1,\ 61)} = 4.1335$, $p < 0.05$; $P_{\mathrm{BIC}}(H_0|D) = 0.51$] indicating lower accuracy for search in large sets (95.6%) than in small sets (96.2%).

Practice effects

As for response times, we analyzed accuracies for practice effects. A main effect of block indicated that participants performed more accurately with increasing numbers of blocks [95.4, 95.2, 96, and 96.9% for blocks 1, 2, 3, and 4, respectively; $F_{(3,\ 183)} = 6.4875$, $p < 0.001$, $P_{\mathrm{BIC}}(H_0|D) = 0.0011$]. Practice had, however, no significant influence on the magnitude of the set size effect [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.82$]. Similarly, the second type of practice analyses revealed a significant increase in performance with practice [$F_{(1,\ 20)} = 6.503, p < 0.05$; $P_{\mathrm{BIC}}(H_0|D) = 0.174$].

DISCUSSION

The observed response times and accuracies gave no indication that attentional disengagement was different for the different postures. Moreover, the lap and screen postures, which lead to significantly different set size effects in Experiment 1 of Abrams

Table 1 | Mean set size differences (mean response times for setsize 8–setsize 4) and corresponding standard errors in parentheses for the postures of Experiments 1–4.

	Postures			
Experiment 1	**Lap**	**Screen**	**Pray**	**Post**
	87 (7.5)	95 (7.4)	80 (6.7)	90 (8.7)
Experiment 2	**Lap***	**Screen***		
	72 (10.1)	100 (16.4)		
Experiment 3	**Lap**	**Screen**	**Release**	**Board**
	48 (5.6)	61 (7.9)	50 (7.5)	41 (5.1)
Experiment 4	**Lap**	**Screen**	**Release**	
	105 (7.1)	108 (9.5)	91 (8.6)	

**significant posture difference.*

Table 2 | Mean percent correct and corresponding standard errors in parentheses for the conditions of Experiments 1–4.

		Postures			
Experiment 1	**Set size**	**Lap**	**Screen**	**Pray**	**Post**
	large	95.1 (0.72)	95.1 (0.66)	95.9 (0.66)	96.2 (0.6)
	small	96 (0.59)	95.7 (0.72)	97 (0.46)	96.1 (0.52)
Experiment 2	**Set size**	**Lap**	**Screen**		
	large	95.2 (0.97)	96 (0.82)		
	small	96.7 (0.6)	96.7 (0.76)		
Experiment 3	**Set size**	**Lap**	**Screen**	**Release**	**Board**
	large	96.3 (0.74)	96.3 (0.63)	96.4 (0.89)	96 (0.7)
	small	96.8 (0.61)	96.6 (0.61)	97 (0.62)	96 (0.56)
Experiment 4	**Set size**	**Lap**	**Screen**	**Release**	
	large	96.4 (0.73)	96.2 (0.68)	96.4 (0.55)	
	small	95.7 (0.75)	96.9 (0.51)	96.8 (0.71)	

et al. (2008) showed no clear sign of differential attentional disengagement. This failure to replicate the originally reported difference between the lap and screen condition renders it problematic to interpret the presence or absence of differences in attentional disengagement between all postures.

Accordingly, one approach might be to restrict analyses of the influence of the different determinants to those participants that show the disengagement effect reported by Abrams et al. (2008), that is, those participants that exhibit a stronger set size effect in the screen condition than in the lap condition. The logic here would be something like: Given that this subset of participants showed a difference in the screen and lap conditions, how then do their other conditions compare? While this logic is sound, such a split may be misleading, however, because it may artificially introduce significant effects between postures. To see this, assume a situation in which the hand posture has **no** influence on the measured response time differences. Due to noise, set size effects will rarely ever be exactly identical across the four postures. Therefore, each participant can be categorized as showing one of 24 (4!) possible orders of the postures in terms of the magnitudes of the set size effect. For example, a participant may exhibit the order lap < pray < post < screen and another may exhibit the order pray < screen < lap < post. For half of all possible orders the relation lap < screen holds. Selecting replicators therefore, amounts to reducing the set of possible orders from 24 to 12. This is problematic, because the relations pray < screen, post < screen, lap < pray, and lap < post each occur in 8 of the 12 orders. Accordingly, selecting replicators may introduce a bias to find evidence for these orderings, even if actually no systematic differences exist between postures. Therefore, an analysis restricted to replicators cannot remedy the problem of a missing difference between lap and screen postures. We are left to conclude that our first experiment was unsuccessful in examining the differential impact of proximity, spanning, and palms on attentional disengagement.

We note that our failure to replicate the difference across the screen and lap postures was not due to a lack of statistical power. The Bayesian analyses revealed that the posterior probability for the H_0 (no differences in set size effects between postures) was considerably higher than the posterior probability of the H_1. Put differently, given the posterior probabilities for the two hypotheses, the experimental results provided positive support (see Masson, 2011) for a lack of an effect of posture on attentional disengagement. Furthermore, although additional analyses indicated the presence of practice effects, we found no clear evidence that these practice effects were responsible for our failure to replicate.

Accordingly, Experiment 2 sought to uncover why we failed to replicate the basic screen and lap posture difference observed robustly across several studies (Abrams et al., 2008; Davoli and Abrams, 2009; Tseng and Bridgeman, 2011). Two aspects of our experimental setup seemed likely candidates. First, in contrast to the study of Abrams et al. (2008), our experiment employed 4 instead of 2 button postures. Second, although the experimental task was the same as in Abrams et al. (2008), there were several differences in operationalization. Specifically, our experiment employed a bigger monitor (20″) than the original study (18″); we used 64 trials per block and the fixation cross disappeared with the onset of the search array, whereas Abrams et al. (2008) used 128 trials per block and the fixation cross remained on the screen during search. Finally, in order to implement the pray and post postures we needed to add wooden constructions to allow us to position the response buttons in the appropriate locations; no such constructions were present in the visual search experiments of Abrams et al. (2008). To investigate the extent to which these differences were responsible for the elimination of the original effect our second experiment employed only the lap and screen postures and reduced the differences in operationalization.

EXPERIMENT 2

The goal of Experiment 2 was to replicate the findings of Abrams et al. (2008), using a physical setup as similar as possible to the original setup. Specifically, we employed the lap and screen postures as shown in **Figures 3B,D**, we replaced the 20″ CRT monitor by a 19″ TFT monitor, increased the number of trials from 64 trials per block to 128 trials per block and removed the wooden constructions that were necessary for the pray and post conditions.

METHODS

Participants

Twenty-four University of Bremen undergraduates participated in Experiment 2. They received a monetary compensation for their participation.

Materials and apparatus

The 20″ CRT monitor was replaced by a 19″ TFT monitor. Response buttons were 3 cm in diameter and were connected to the computer as an additional keyboard device such that pressing the buttons produced the characters "/" and "z," respectively. All other materials and apparatus were identical to those in Experiment 1.

In this setup, the distance between the two hands was 30 cm and 31 cm in the lap and screen postures, respectively. The distance of the hands to the monitor was 45 cm in the lap posture and the distance between the viewer and the hands was also 45 cm in the screen posture.

Procedure

Trials proceeded as described for Experiment 1 with the exception that the fixation cross remained on the screen during the whole trial. Overall, each participant performed 256 trials that were presented in blocks of 128 trials. For each block the hands were in a different posture such that both of the postures lap and screen (see **Figure 3**) were used for exactly one block. The order of postures was counterbalanced across subjects.

RESULTS

Response times

Trials in which participants answered incorrectly were excluded from response time analyses. Furthermore, standard deviations and means were computed for each individual and condition and response times outside a 2.5 $*$ *SD* range from the mean were excluded from analyses. Overall 7% of all trials were excluded from analyses.

Figure 4B and **Table 1** show the mean response times and the set size effects, respectively, for the two postures. A 2 (posture) × 2 (set size) analysis of variance revealed that search was faster in small ($M = 530$ ms) than in large ($M = 616$ ms) sets [$F_{(1,\ 23)} = 49.162$, $p < 0.001$; $P_{\mathrm{BIC}}(H_0|D) < 10^{-6}$]. Furthermore, the significant posture × size interaction [$F_{(1,\ 23)} = 5.9$, $p < 0.05$; $P_{\mathrm{BIC}}(H_0|D) = 0.24$] indicated that the set size effect was smaller for the lap posture (mean response time difference of 72 ms) than the set size effect for the screen posture (mean response time difference of 100 ms). There was no significant main effect of posture on response times [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.812$].

Practice effects

There were no clear practice effects: neither the main effect of block [$F_{(1,\ 23)} = 1.9575$, $p > 0.15$; $P_{\mathrm{BIC}}(H_0|D) = 0.65$] nor the block × set size interaction [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.75$] were significant.

Accuracies

Table 2 shows the mean accuracies for the lap and the screen posture. Accuracies ranged from 84% to 100% with a mean accuracy of 96%. A 2 (posture) × 2 (set size) analysis of variance revealed no effect of posture [$F_{(1,\ 23)} = 2.757$; $P_{\mathrm{BIC}}(H_0|D) = 0.557$] and no interaction [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.83$]. The main effect of size approached significance [$F_{(1,\ 23)} = 4.007$, $p < 0.06$; $P_{\mathrm{BIC}}(H_0|D) = 0.416$] indicating a slightly lower accuracy for search in large sets (95.6%) than for search in small sets (96.7%).

Practice effects

There were no clear practice effects: neither the main effect of block [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.82$] nor the block × set size interaction [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.81$] were significant.

DISCUSSION

The results of Experiment 2 replicate Abrams et al. (2008), using 2 postures and an operationalization of the procedure that closely mimicked the original study. The aim of Experiment 3 was thus, to examine whether the failure to replicate the original effect in Experiment 1 was due to its inclusion of an increased number of postures. Accordingly, we used the operationalization of the procedure from Experiment 2 but added two postures to the lap and screen postures. The extra postures, called board (**Figure 3A**) and release (**Figure 3C**), were chosen such that they did not require any additional hardware constructions. As a result, though employing two extra postures, the physical setup in Experiment 3 was the same as in Experiment 2 (see **Figure 3**); in addition, the procedural changes (e.g., fixation cross present through the trial; 128 trials per block) were as in Experiment 2. If the addition of these postures leads to the extinction of the effect, this would provide evidence that the number of postures was responsible for the failure to replicate. If, in contrast, the original effect is replicated, the postures board and release would allow investigating the impact of the determinants of proximity and response direction. If proximity is of importance, there should be a significantly increased set size effect in the board posture compared to the lap posture. If response direction influences attentional disengagement, there should be a larger set size effect in the screen posture than the release posture.

EXPERIMENT 3

Experiment 3 employed the four postures board, lap, release, and screen as shown in **Figures 3A–D**, respectively, but otherwise employed the same physical setup and operationalization as Experiment 2.

METHODS

Participants

Twenty-four University of Notre Dame undergraduates participated in Experiment 3. They were compensated by partial credit for an undergraduate psychology course.

Materials and Apparatus

Materials and Apparatus were the same as in Experiment 2, but distances differed slightly. The distance between the two hands was 37 cm for the screen and release postures and 40 cm for the board and lap postures. The distance of the hands to the monitor was 60 cm in the lap posture and 4 cm in the board posture. The distance between the viewer and the hands was 39 cm in the board posture and 35 cm in the screen and release postures.

Procedure

Trials proceeded as described for Experiment 2. Overall, each participant performed 512 trials that were presented in blocks of 128 trials. For each block the hands were in a different posture such that each of the four postures board, lap, release, and screen (see **Figure 3**) was used for exactly one block. The order of postures was counterbalanced across subjects.

RESULTS

Response times

Trials in which participants answered incorrectly were excluded from response time analyses. Furthermore, standard deviations and means were computed for each individual and condition and response times outside a $2.5 * SD$ range from the mean were excluded from analyses. Overall 6% of all trials were excluded from analyses.

Figure 4C and **Table 1** show the mean response times and set size differences, respectively, for the four postures. A 4 (posture) × 2 (set size) analysis of variance revealed that search was faster in small ($M = 521$ ms) than in large ($M = 571$ ms) sets [$F_{(1,\ 23)} = 0.131.93$, $p < 0.001$; $P_{\text{BIC}}(H_0|D) < 10^{-9}$] and that responses were slower in the release posture than in the other postures [Ms = 525, 542, 581, and 535 ms for board, lap, release, and screen postures, respectively; $F_{(3,\ 69)} = 17.95$, $p < 0.001$; $P_{\text{BIC}}(H_0|D) < 10^{-8}$]. However, there was no significant interaction [$F_{(3,\ 69)} = 1.96$, $p > 0.1$, $P_{\text{BIC}}(H_0|D) = 0.308$], suggesting that the set size effect was not mediated by posture, (Ms = 41, 48, 50, and 61 ms for board, lap, release, and screen, respectively). In particular, the set size effects in the lap and the screen postures did not differ significantly [$F_{(1,\ 23)} = 2.35$, $p > 0.1$, $P_{\text{BIC}}(H_0|D) = 0.603$].

Practice effects

A 4 (block) × 2 (set size) analysis of variance revealed that search got faster with increasing practice [565, 544, 544, and 529 ms for blocks 1, 2, 3, and 4, respectively; $F_{(3,\ 69)} = 4.5517$, $p < 0.01$, $P_{\text{BIC}}(H_0|D) = 0.013$]. The interaction did not reach significance [$F < 1$, $P_{\text{BIC}}(H_0|D) = 0.809$], indicating that practice had no clear impact on the magnitude of the set size effect. A 2 (posture) × 2 (set size) × 2 (presentation time) analysis of variance found no evidence for increased search speed with practice [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.703$] nor any significant interaction involving presentation time.

Accuracies

Table 2 shows the mean accuracies for the four postures. Accuracies were again high, ranging from 90% to 99% with a mean accuracy of 96%. A 4 (posture) × 2 (set size) analysis of variance revealed no effect of posture [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.685$], no effect of size [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.83$], and no significant interaction [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.849$].

Practice effects

There were no clear practice effects: neither the main effect of block [$F_{(3,\ 69)} = 1.6538$, $p > 0.15$; $P_{\text{BIC}}(H_0|D) = 0.41$] nor the block × set size interaction [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.734$] were significant. Similarly, the second set of practice analyses yielded no indication of an influence of practice on accuracy [$F < 1$; $P_{\text{BIC}}(H_0|D) = 0.739$] or on the magnitude of the set size effect (no interaction involving presentation time reached significance).

DISCUSSION

Despite the increased similarity of the experimental setup to the original study of Abrams et al. (2008), results largely mirrored those of Experiment 1. In particular, there was no clear indication of a differential effect of posture on attentional disengagement—neither across all postures nor when only comparing lap and screen postures. Furthermore, analyses render it unlikely that the lack of a disengagement effect is due to practice effects. The only difference in results between Experiment 1 and Experiment 3 is the main effect of posture that arose from slowed responding in the release posture. Based on personal experience running through the experiment and spontaneous comments by participants, this slowing may have been due to the unfamiliar response mode of releasing instead of pressing the response buttons.

In the light of these results and the results of the previous two experiments, it seemed more likely that the absence of an attentional disengagement effect was due to the increased number of postures than due to dissimilarities in experimental setups. To further assess the sensitivity of the disengagement effect to the number of additional postures, we employed only one extra posture, the release posture, in Experiment 4. The release posture was chosen because this posture allowed using the same button configurations as in Experiment 2 (thus, rendering the setup of Experiment 4 identical to the setup of Experiment 2) while also adding a new response direction. In addition, Experiments 1 and 3, which failed to replicate were run at the University of Notre Dame while the first author was visiting during a research stay, and Experiment 2 was run at the University of Bremen. Thus, being run at the University of Bremen, Experiment 4 enabled us to check whether the failure to replicate in Experiments 1 and 3 was due to population differences.

EXPERIMENT 4

METHOD

Materials, apparatus, and procedure were identical to those in Experiment 2 and 3. Distances were the same as in Experiment 2.

Thirty University of Bremen undergraduates participated in Experiment 4. They chose to receive either monetary compensation or partial credit for an undergraduate psychology course for their participation.

RESULTS

Response times

Trials in which participants answered incorrectly were excluded from response time analyses. Furthermore, standard deviations and means were computed for each individual and condition and response times outside a 2.5 $*$ *SD* range from the mean were excluded from analyses. Overall 6% of all trials were excluded from analyses.

Figure 4D and **Table 1** show the mean response times and the set size effects, respectively, for the three postures. As can be seen from the figure, the results largely mirrored those of Experiment 3. A 3 (posture) × 2 (set size) analysis of variance revealed that search was faster in small (556 ms) than in large (657 ms) sets [$F_{(1,\ 27)} = 200.62$, $p < 0.001$; $P_{\mathrm{BIC}}(H_0|D) < 10^{-13}$]. Furthermore, response speed differed significantly across postures [$F_{(2,\ 58)} = 11.716$, $p < 0.001$; $P_{\mathrm{BIC}}(H_0|D) < 0.001$] with responses in the release posture being considerably slower (635 ms) than responses in the lap (589 ms) and the screen (596 ms) posture. However, there was no significant interaction, indicating that posture did not mediate the set size effect (*M* set sizes = 105, 91, and 108 ms for lap, release, and screen postures, respectively), either for all three postures [$F_{(2,\ 58)} = 2.588$, $p > 0.08$; $P_{\mathrm{BIC}}(H_0|D) = 0.373$] or when only considering postures lap and screen [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.834$].

Practice effects

A 3 (block) × 2 (set size) analysis of variance indicated no clear main effect of block [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.784$] and no significant block × set size interaction [$F_{(2,\ 58)} = 2.48$, $p > 0.09$; $P_{\mathrm{BIC}}(H_0|D) = 0.398$]. The 2 (posture) × 2 (set size) × 2 (presentation time) analysis of variance also did not yield any significant effect of practice on search speed [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.807$] or the magnitude of the set size effect (no interaction including the factor presentation time reached significance).

Accuracies

Table 2 shows the mean accuracies for the three postures. Accuracies ranged from 85% to 99% with a mean accuracy of 96%. A 3 (posture) × 2 (set size) analysis of variance revealed no effect of either posture [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.884$] or set size [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.837$]. The interaction also did not reach significance [$F_{(2,\ 58)} = 2.097$, $p > 0.1$; $P_{\mathrm{BIC}}(H_0|D) = 0.49$].

Practice effects

A 3 (block) × 2 (set size) analysis of variance revealed that participants performed more accurately with increasing practice [95.8, 96.4, and 97% for blocks 1, 2, and 3, respectively; $F_{(2,\ 58)} = 8.7924$, $p < 0.001$; $P_{\mathrm{BIC}}(H_0|D) = 0.003$]. The interaction did not reach significance [$F_{(2,\ 58)} = 1.933$, $p > 0.15$; $P_{\mathrm{BIC}}(H_0|D) = 0.528$], indicating that practice had no clear impact on the magnitude of the set size effect. As for response times, a 2 (posture) × 2 (set size) × 2 (presentation time) analysis of variance did not indicate any substantial practice effects: Neither the main effect of presentation time [$F < 1$; $P_{\mathrm{BIC}}(H_0|D) = 0.786$] nor any of its interactions reached significance.

DISCUSSION

As in Experiments 1 and 3, there was no clear indication of a differential modulation of the disengagement of attention depending on posture, even when practice effects were taken into account. This suggests that even a single additional posture was enough to eliminate the disengagement effect reported in Abrams et al. (2008) and replicated in Experiment 2. Furthermore, since the extinction of the original effect occurred across two different sites (University of Notre Dame and University of Bremen), it is unlikely that the failure/success of replication is due to population differences.

GENERAL DISCUSSION

Although we were able to replicate the modulation of the disengagement of attention by different hand postures originally reported by Abrams et al. (2008) in one of our experiments (Experiment 2), we found no evidence of such a modulation in the other three experiments we conducted: Whenever the experimental design included more than the originally employed lap and screen postures, the disengagement effect disappeared (Experiments 1, 3, and 4). Given the properties of our experiments it seems unlikely that the disappearance of the modulation is due to (a) the particular postures added to the lap and screen postures (pray, **Figure 2B**, and post, **Figure 2C**, were used in Experiment 1, board, **Figure 3A**, and release, **Figure 3C**, postures were used in Experiment 3 and 4), (b) the population under investigation (Experiment 1 and 3 drew on US students at the University of Notre Dame, while Experiment 4 drew on German students at the University of Bremen), or (c) the physical setup of the experiments (compare setups of Experiment 1, **Figure 2**, vs. setups of Experiments 3 and 4, **Figure 3**). Furthermore, Bayesian analyses ruled out the possibility that the failure to find an attentional disengagement effect in Experiments 1, 3, and 4 is a result of a lack in statistical power: In all three experiments the a-posteriori probability of the null hypothesis that there is no difference in attentional disengagement between the lap and screen postures is considerably higher than the probability of the alternative hypothesis [$P_{\mathrm{BIC}}(H_0|D) = 0.85$, 0.603, and 0.834 for Experiments 1, 3, and 4, respectively]. As an additional test we analyzed the pooled data of Experiments 3 and 4 for the postures lap, release, and screen. Again, there was no evidence of an attentional disengagement effect; neither when comparing response time differences for the lap ($M = 80$ ms) and the screen ($M = 87$ ms) postures [$F_{(1,\ 53)} = 1.6834$, $p > 0.2$; $P_{\mathrm{BIC}}(H_0|D) = 0.76$] nor when comparing accuracy differences for the lap (0.14%) and the screen (−0.55%) postures [$F_{(1,\ 53)} = 1.955$, $p > 0.15$; $P_{\mathrm{BIC}}(H_0|D) = 0.734$].

This leaves the number of postures as the most credible cause for the disappearance of the attentional disengagement effect, such that the addition of an extra posture eliminated the effect observed across the screen and lap conditions. It is, however, currently unclear why this addition leads to the extinction of the effect.

The setup of the four experiments and analyses results rule out a number of explanations. First, it seems unlikely that the disappearance of the effect is due to an increase in the number of trials that results from an increase in the number of postures. In Experiment 1, participants worked on 64 search trials for each of the four postures and, thus, participants performed 256 search trials overall. The same number of search trials was performed by participants in Experiment 2, because for each of the two postures employed in this experiment, participants completed 128 trials. Accordingly, the difference in replication between the two experiments cannot be due to the overall number of search trials.

Second, results suggest that practice does not play a major role in the disappearance of the disengagement effect. Although practice led to reduced set size effects in Experiments 1, we found no evidence that this decrease caused the extinction of the disengagement effect.

Third, it is unlikely that the extinction of the effect is brought about by an increased likelihood of guessing the purpose of the experiment due to experiencing more postures. If experiencing more postures were responsible for the disappearance of an otherwise present effect, the effect should be detectable when analyzing only the data from the lap and screen postures of those participants that experienced these postures in the first two blocks. However, conducting such analyses revealed no clear evidence for an influence of hand postures on the set size effect.

Although the sequence of experiments and their results were not as we initially anticipated, they provide an interesting and novel answer to the question that motivated our work: "What are the situational determinants for attentional disengagement?" Our results indicate that it is not only the nature of hand postures, but also the number of postures that impacts the presence or absence of attentional disengagement. That is, the number of postures itself constitutes one of the situational determinants of the attentional disengagement effect. This is in line with the fact that previous studies on attentional disengagement did not employ more than two hand postures (Abrams et al., 2008; Pollux and Bourke, 2008; Davoli et al., 2012).

Against this background it seems interesting to consider whether this situational determinant (number of postures) is specific to attentional disengagement or whether it may more generally impact a wider range of modulations of visual processing. In fact, some experiments (Reed et al., 2006, 2010; Experiment 1 of Davoli and Brockmole, 2012; Experiment 4 of Dufour and Touzalin, 2008) found an effect of the hands on attentional prioritization although they employed more than two hand postures. Accordingly, while more than two hand postures led to an elimination of the attentional disengagement effect in the current work, an increased number of postures had no comparable effect on attentional prioritization—at least not in those experiments reported in the literature. To what extent the number of postures constitutes a critical determinant for other effects the hands can have on visual processing is currently hard to judge, because the majority of previous experiments do not employ more than two hand postures within participants (Vishton et al., 2007; Cosman and Vecera, 2010; Linkenauger et al., 2010; Tseng and Bridgeman, 2011; Experiments 1–3 in Dufour and Touzalin, 2008; Experiment 2 in Davoli et al., 2010; Davoli and Brockmole, 2012; Gozli et al., 2012).

In conclusion, our experiments highlight the potential importance of the number of postures as another crucial situational determinant for the impact one's hands have on various aspects of visual processing. Given that previous studies have not systematically investigated this determinant suggests that its importance may have been underestimated so far. Our results stress the necessity to explicitly consider this factor and future work is required to examine to what extent the number of postures also influences the other effects that hands may have on visual processing.

AUTHOR NOTE

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Prolonged disengagement from distractors near the hands

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Because items near our hands are often more important than items far from our hands, the brain processes visual items near our hands differently than items far from our hands. Multiple experiments have attributed this processing difference to spatial attention, but the exact mechanism behind how spatial attention near our hands changes is still under investigation. The current experiments sought to differentiate between two of the proposed mechanisms: a prioritization of the space near the hands and a prolonged disengagement of spatial attention near the hands. To differentiate between these two accounts, we used the additional singleton paradigm in which observers searched for a shape singleton among homogenously shaped distractors. On half the trials, one of the distractors was a different color. Both the prioritization and disengagement accounts predict differently colored distractors near the hands will slow target responses more than differently colored distractors far from the hands, but the prioritization account also predicts faster responses to targets near the hands than far from the hands. The disengagement account does not make this prediction, because attention does not need to be disengaged when the target appears near the hand. We found support for the disengagement account: Salient distractors near the hands slowed responses more than those far from the hands, yet observers did not respond faster to targets near the hands.

Keywords: visual attention, visual processing near hands, attentional capture, attentional control, hand position

Interacting with objects in the real world requires several cognitive and perceptual processes to be integrated. Consider the simple example of picking up your coffee cup: This seemingly simple act requires (1) coordination between a visual representation of the object's shape and spatial location (necessary for basic visual perception), (2) selective (attentional) processing to the object (necessary to minimize interference from other objects), and (3) the current state and position of one's body (necessary for planning a movement). Although interacting with objects may require other perceptual-cognitive operations, both spatial attention and body position are critical for the initial localization of and interaction with objects in everyday situations. Understanding how the body guides and interacts with visual inputs in directing spatial attention is important for accounts of real-world behavior.

Bimodal neurons in premotor and parietal cortex have visual receptive fields that surround part of the body (e.g., the hand), and this visual receptive field shifts in space as the body part moves (Graziano and Gross, 1993, 1998). One potential behavioral consequence of these neurons is that body position affects cross modal spatial attention as well as visual inputs. Recent behavioral studies have demonstrated that the body indeed influences spatial attention, both in neurologically normal participants (for a review, see Brockmole et al., 2013) and brain-damaged patients with attentional disruptions (di Pellegrino and Frassinetti, 2000; Schendel and Robertson, 2006). Although hand position affects spatial attention, the mechanisms of this influence are still the focus of active study. Some accounts propose that the body prioritizes attention in the direction of the hand (Reed et al., 2006), whereas others hypothesize that hand position influences perceptual-level processing (Cosman and Vecera, 2010). Further, some accounts argue that hand position influences specific attentional operations, such as attentional disengagement (Abrams et al., 2008), or biases processing toward certain types of information, such as high temporal frequencies (Gozli et al., 2012).

The current experiment aims to distinguish whether the body prioritizes attention toward the hand or slows the disengagement from items near the hand. To differentiate between these two accounts, we turned to the additional singleton paradigm (Theeuwes, 1992; see Theeuwes, 2010, for a review). In the additional singleton paradigm, observers look for a shape singleton target among homogenous distractors (e.g., a circle among diamonds) and respond to an irrelevant feature of the target (orientation of a line within the target). Importantly, on half the trials, one of the distractors is a different color (i.e., a color singleton). The target is never a color singleton, so there is no reason to attend to the color singleton, so if attentional control is perfectly tuned for an observer's goals, then observers should devote no processing to this color singleton distractor. Interestingly, researchers consistently find observers respond slower to the target when the color singleton is present than when it is absent (Theeuwes, 2010), and these slower response times reflect processing of the color singleton. Thus, to differentiate whether hand position modulates attentional prioritization or disengagement, we used the additional singleton paradigm in Experiment 1A. We reasoned that both the attentional prioritization and disengagement accounts predict observers will respond to the target slower when the color singleton appears near the hand than when it appears far from the hand because items near the hand are either prioritized or disengagement from these items is prolonged. Critically, the attentional prioritization account also predicts that because the space near the hands is prioritized, observers will respond faster to targets near the hands than far, but the disengagement account does not make this prediction.

It is possible hand position will have a small effect on task performance because the additional singleton paradigm traditionally uses consistently defined target and distractors, which encourages observers to guide attention based on the task features (Lamy et al., 2006). That is, observers might rely on a well-learned target template for the circle target, thereby minimizing the hand's overall influence. Thus, to fully evaluate the target prioritization account, it is critical to prevent attentional guidance by features. To discourage observers from guiding search based on target and distractor features, we used the mixed version of the additional singleton paradigm in Experiment 1B (Pinto et al., 2005). In this version of the task, the target/distractor identities and object colors change from trial to trial. For example, on one trial, the target could be defined as a circle among diamonds and on the next it could be a diamond among circles. Additionally, the color of the target changes from trial to trial. These changes minimize the opportunity for observers to guide attention based on a target template (i.e., a specific shape or color feature) other than a singleton search mode (Pashler, 1988).

To investigate whether attention is prioritized near the hands or attention is slower to disengage from items near the hands, half the observers completed the additional singleton paradigm with either their left or right hand near the screen. The other half of participants completed the mixed version of the additional singleton paradigm with either their left or right hand near the screen. Slower responses to the target when the color singleton was near the hand than far from the hand will serve as a manipulation check because both accounts predict this. Critically, if attention is prioritized to items near the hands, then observers should be faster to respond to targets near the hands than far, but if observers are slower to disengage from items near the hands, then observers will not respond faster to items near the hands than far.

METHODS

OBSERVERS

Thirty-two undergraduate students from the University of Iowa participated to fulfill a course requirement. Sixteen participated in Experiment 1A and sixteen participated in Experiment 1B. All observers reported normal or corrected-to-normal vision.

STIMULI AND PROCEDURE

A Mac Mini computer with a 17-in CRT monitor presented stimuli and collected response through MATLAB and the Psychophysics Toolbox (Brainard, 1997). Eight stimuli were presented around an imaginary circle centered on the screen with a radius of 6°. The stimuli consisted of seven diamonds and one circle. The stimuli were each approximately $2.8 \times 2.8°$. Each item contained either a gray vertical or horizontal line. The lines measured $1.5 \times 0.3°$. In Experiment 1A, all the items were green (RGB 20 210 5) except on half the trials, one of the diamonds was red (RGB 255 0 0). In Experiment 1B, the color (red or green) and shape (circle or diamond) of the target was chosen randomly on each trial. A white fixation dot was presented at the center of the screen and measured $0.6 \times 0.6°$. Additionally, two white dots ($0.6 \times 0.6°$) were presented on the left and right sides of the screen. These dots indicated where observers' hands should place their hands.

The target appeared equally often at any of the eight possible target positions. Observers responded to the orientation of the gray line within the target. Observers responded with a left pedal if the target contained a vertical line and they responded with a right foot pedal if the target contained a horizontal line. Half the trials contained a target with a horizontal line and half the trials contained a target with a vertical line. A color singleton distractor was present on half the trials. The color singleton distractor appeared randomly at one of the seven positions not already occupied by the target.

On half the blocks the observers held their right hand up with their middle finger abutting the monitor. The palm of their hand faced toward the search array. On the other half of the blocks, observers held their left hand near the monitor. Observers' arms were supported by armrests to prevent fatigue. The order of which hand was initially held up to the monitor was counterbalanced across observers. The blocks were 28 trials long and each experimental session consisted of 896 trials. Observers were given a self-paced break at the end of each block. Finally, to keep the displays as visually balanced as possible, a visual anchor abutting the monitor was always presented opposite to the raised hand.

Each trial started with the presentation of a fixation dot and the two dots indicating hand placement for a second. Following this, the search array was presented for 3 s or until response (see **Figure 1**). If observers took more than 3 s to respond, the trial was scored as incorrect and observers were encouraged to respond faster. Observers were instructed to maintain fixation and to respond as quickly and accurately as possible. Observers completed four practice blocks of trials (two with each hand up) before the experimental session.

RESULTS AND DISCUSSION

Incorrect responses and RTs more than 2.5 standard deviations from an observers' condition mean were excluded from the analysis. This eliminated 1.6% of the data in Experiment 1A and 1.1% of the data in Experiment 1B. We submitted mean RTs to a mixed ANOVA with the within subject factors item near hand (Target or Distractor) and distance from hand (Near or Far). Experiment (1A or 1B) was a between subjects factor. To prevent any interference due to target and color singleton proximity (Mounts, 2000a,b), RTs in this analysis only included trials in which the target was present at one of the two positions on the vertical meridian and the color singleton was present in one of the two positions on the horizontal meridian when evaluating the effect of hand position on distractor processing and vice versa when evaluating the effect of hand position on target processing. Slower responses when the distractor was on the horizontal meridian than when the target was on the horizontal meridian drove a main effect of the item near hand factor, $F_{(1,30)} = 31.21$, $p < 0.001$. As expected, the item near hand factor interacted with the experiment factor, $F_{(1,30)} = 15.05$, $p = 0.001$, because,

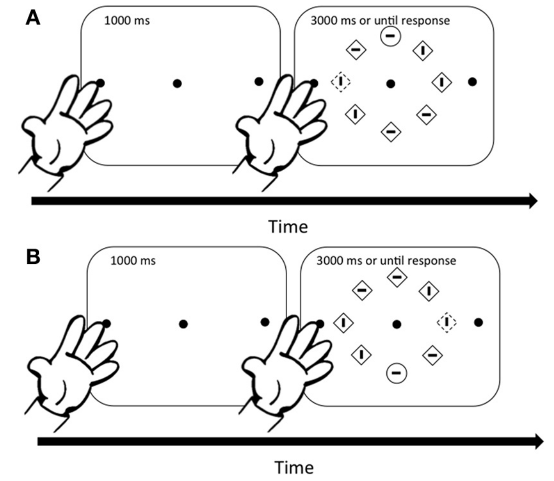

FIGURE 1 | Sequence of events for Experiments 1A,B. A fixation dot preceded each search display by 1000-ms. The search display remained on the screen for 3000-ms or until response. Color singletons appeared on 50% of the trails. In **(A)** the color singleton appears on the horizontal meridian near the hand and the target appears on the vertical meridian. In **(B)**, the color singleton appears on the horizontal meridian far from the hand and the target appears on the vertical meridian.

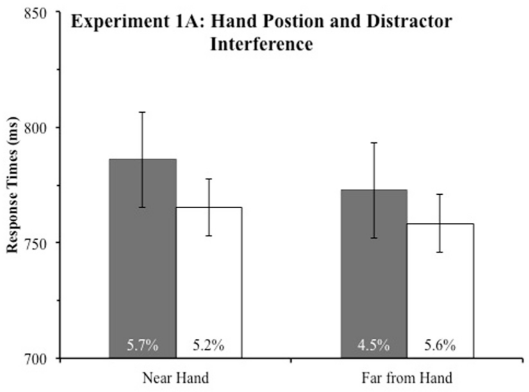

FIGURE 2 | Experiment 1A response times (in ms) as a function of item near hand (target or distractor) and distance from hand (near the hand or far from the hand). The error rates of each condition are reported in the base of the bars. Error bars represent 95% within-subject confidence intervals (Loftus and Masson, 1994).

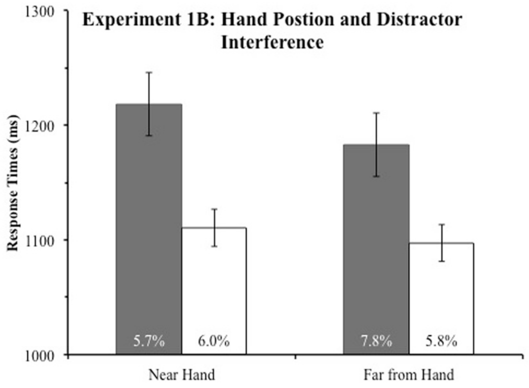

FIGURE 3 | Experiment 1B response times (in ms) as a function of item near hand (target or distractor) and distance from hand (near the hand or far from the hand). The error rates of each condition are reported in the base of the bars. Error bars represent 95% within-subject confidence intervals (Loftus and Masson, 1994).

as depicted in **Figures 2**, **3**, color singletons slowed responses more in Experiment 1B (mixed additional singleton design) than in Experiment 1A (fixed additional singleton design). Observers responded slower when the target or distractor appeared near the hand, $F_{(1,30)} = 3.83$, $p = 0.06$, demonstrating that the hand had an effect. Slower responses to the target when the distractor is near the hand than far from the hand (depicted in **Figures 2**, **3**) likely drove this effect. The distance from the hand factor did not interact with the experiment factor, $F_{(1,30)} = 0.65$, $p > 0.42$, demonstrating that the hand had the same effect in the two experiments.

Interestingly, suggesting that the observers were slower to respond both when the target was near the hand and when the distractor was near the hand, the item near hand factor (target or distractor) and the distance from the hand factors did not interact, $F_{(1,30)} = 0.5$, $p > 0.47$. The three way interaction between item near hand, distance from hand, and experiment also failed to reach significance, $F_{(1,30)} = 0.16$, $p > 0.68$. Although the non-significance of these interactions suggests hand position did not speed responses to items near the target, because this is a central question of our study, we conducted follow up analyses to investigate differences in RTs to targets near and far from the hands in each experiment.

To evaluate the effect of hand position on target processing, we compared RTs when the target was on the horizontal meridian and the distractor, when present, was on the vertical meridian. Thus, we conducted a *t*-test comparing mean RTs to targets on the horizontal meridian near and far from the hand. Inconsistent with the prioritization account, in Experiment 1A, we found RTs to the target were no faster when the target was near the hand (765 ms) than far (758 ms), $t_{(15)} = 0.60$, $p > 0.55$. It is possible this *t*-test failed to find a difference because hand position has a different effect on target processing when the color singleton is present than absent, so we performed two additional *t*-tests on RTs from Experiment 1A, one comparing RTs to targets near and far from the hand when the color singleton was absent, $t_{(15)} = 0.51$, $p > 0.61$, and another when the color singleton was present, $t_{(15)} = 0.37$, $p > 0.72$. Thus, these tests falsify the prioritization account and lend tentative support to the disengagement account of hand position's effect on cognition.

To evaluate if hand position affected responses to the target in Experiment 1B, we ran the same *t*-tests as in Experiment 1A. Again, the results falsified the prioritization account since RTs to the target did not differ when the color singleton was near (1097 ms) and far from the hand (1110 ms), $t_{(15)} = 0.87$, $p > 0.4$. Again, responses to targets near and far from the hand did not depend on the presence or absence of the color singleton because these *t*-tests also failed to reach significance [Absent: $t_{(15)} = 0.004$, $p > 0.99$; Present: $t_{(15)} = 0.76$, $p > 0.45$]. Thus, our experiments demonstrate that observers were no faster to respond to targets near their hands, which is inconsistent with an attentional prioritization of items near the hand account and lends tentative support to the slowed disengagement from items near the hands account.

We repeated all RTs analyses with arcsine-transformed error rates. The mixed ANOVA and planned follow-up comparisons all failed to reach significance. We suspect these comparisons failed to reach significance because accuracy values were so close to ceiling. Importantly, the lack of significant values also demonstrates that the RT differences in this experiment cannot be explained by a speed accuracy trade-off.

GENERAL DISCUSSION

The mechanism behind hand position's effect on visual attention is an open question and the current experiment sought to differentiate between the prioritization of items near the hands (Reed et al., 2006) and prolonged disengagement from items near the hands accounts (Abrams et al., 2008). To differentiate between these accounts, we used the additional singleton paradigm because both accounts predicted greater slowing from color singletons near the hands than far from the hands. Importantly, the prioritization account predicts faster responses to targets near the hands while the disengagement account does not. We rejected the prioritization account and we tentatively support the disengagement account because neither experiment 1A nor experiment 1B found faster responses to targets near than far from the hands while the two experiments did find slower RTs when a distractor or target appeared near the hands than far from the hands.

Our experiments did not seek to evaluate the perceptual-level processing (Cosman and Vecera, 2010) and bias toward high temporal frequency accounts of hand position (Gozli et al., 2012). These accounts are still plausible especially since it is reasonable to speculate that hand position has multiple different effects along the processing stream. Future experiments should evaluate these different accounts of the mechanism behind hand position effects.

One additional explanation of our data is that the color singleton distractors slowed response times not because they captured attention, but because color singletons require more preattentional processing (i.e., a filtering cost; Folk and Remington, 1998). For instance, it is possible that items near the hand take longer to process than items far from the hands, but we find this hypothesis unlikely for a number of reasons. First, ERP evidence supports the attentional capture account of the additional singleton paradigm (Hickey et al., 2006). Second, we believe it is unlikely the cognitive system is designed to process items near the hands slower than items far from the hands because items near the hands are likely important, and, if anything, should be processed faster.

One interesting question is why Reed et al. (2006) found faster detection of targets near the hands, but we did not find faster responses to targets near the hands. It is possible that hand position is simply weighted like any other input to the attentional mechanism (Wolfe, 1994) and that when feature values are important, feature values are more heavily weighted and hand position is less weighted. Thus, in an experiment like Reed and colleagues' it is possible that the sparse displays provided so little information that hand position was more heavily weighted (i.e., prioritized). Basically, we propose that whether the space near the hands is prioritized may interact with the amount of information observers have to complete the rest of the task. When observers have little information to help them complete a task, such as in a Posner cuing task, the space near the hands is prioritized, but when observers are able to guide task performance with information such as target features, the space near the hands is not prioritized. We are currently running experiments to evaluate this possibility.

Because of hand position's importance to many daily activities, spatial attention changes near the hands. The current experiments sought to evaluate between two accounts of exactly how spatial attention changes near the hands. The first account is that the space near the hands is prioritized and the second account is that observers are slower to disengage from items appearing near their hands. We failed to find support for the prioritization account, so we tentatively support the disengagement account that observers are slower to disengage from items near their hands. Thus, our experiments suggest that the hands might not always change the processing of items near the hands and instead hand position might extend the processing of these potentially important items.

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Both hand position and movement direction modulate visual attention

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The current study explored effects of continuous hand motion on the allocation of visual attention. A concurrent paradigm was used to combine visually concealed continuous hand movements with an attentionally demanding letter discrimination task. The letter probe appeared contingent upon the moving right hand passing through one of six positions. Discrimination responses were then collected via a keyboard press with the static left hand. Both the right hand's position and its movement direction systematically contributed to participants' visual sensitivity. Discrimination performance increased substantially when the right hand was distant from, but moving toward the visual probe location (replicating the far-hand effect, Festman et al., 2013). However, this effect disappeared when the probe appeared close to the static left hand, supporting the view that static and dynamic features of both hands combine in modulating pragmatic maps of attention.

Keywords: embodied cognition, covert attention, hand dynamics, near-hand effect, perception

INTRODUCTION

Our visual environment offers more information than we can process and act upon. Although the human visual system is characterized by extensive parallel processing, perception and action operate on one object at a time. Therefore, the ability to selectively attend to a portion of our visual environment is crucial for observers to compensate for their limited cognitive capacity. In the late 1980s, Rizzolatti et al. (1987) challenged the classical notion that selective attention is a structural control mechanism for selecting a certain portion of our visual space for prioritized processing. They proposed instead the "premotor theory of attention," postulating that selective attention is driven by the same frontal-parietal circuits that are involved in the preparation of movements toward specific spatial locations. Accordingly, attentional selection was attributed to spatial pragmatic maps, which in turn depend on the preparation of goal-directed, spatially coded movements. Further studies of the coupling between eye movements and visual selection have found fairly supportive results for this idea (Hoffman and Subramaniam, 1995; Kowler et al., 1995; Deubel and Schneider, 1996; Fischer, 1999; Castet et al., 2006). For example, in a dual task paradigm that required a combination of target-directed saccade and letter-discrimination, performance was best when the discrimination target and saccade target referred to the same item (Deubel and Schneider, 1996).

While initial work explored the links between shifts of attention and oculomotor preparation, premotor theory asserts that the interplay between response programing and attentional selection is by no means restricted to oculomotor activity but can be driven by activity in pragmatic maps involved in programming hand movements (Rizzolatti et al., 1994). Unlike preparing an eye movement, which mainly involves goal selection, hand movement preparation also requires effector selection (i.e., left or right hand) and determining the dynamic position of the selected effector within different regions of space. Therefore, attention involved in preparing hand movements is likely affected by both hand selection and dynamic aspects of the response.

Studies of the association between attention and goal-directed hand movements have found inconsistent results. In a seminal study of the interplay between hand movements and visual selection, Tipper et al. (1992) studied the interference effect of a distractor stimulus while participants were engaged in goal-directed arm movements. They showed that the interference effect was present only when the distractor was located within the space between the start position of the hand and the location of the target, suggesting that visual attention extends from the start to the end position of the planned movement (see also Fischer, 1997). Other studies have instead shown that visual attention is strongly coupled to the response goals. Deubel et al. (1998) used a dual task paradigm to demonstrate that, when observers prepare a reaching movement to a certain location, performance is superior for targets displayed at the movement goal before movement onset. More recent work has revealed that, during the preparation of sequential reaching movements, attention is biased toward multiple goal-relevant locations in parallel (Baldauf et al., 2006). Similar parallel deployment of attention was also observed during the preparation of coordinated bimanual movements (Baldauf and Deubel, 2008). Taken together, these experimental studies suggest that motor preparation is coupled with visual selection of the intended goal locations *ahead* of the current position of the hand.

Complementing research on movement preparation, there is other work demonstrating that the static position of our hands can affect visual selection. Reed et al. (2006, 2010) studied whether the location of one's resting hand affects attentional selection. Participants placed one hand on a computer monitor and were faster in detecting probes near their hand (see also Adam et al., 2012; Gozli et al., 2012). Cosman and Vecera (2010) have shown that, in addition to prioritizing attention, the position of the observers' hand facilitates figure-ground segregation. Another demonstration of the influence of hand position on visual sensitivity has been revealed with a patient with a severe left hemianopsia. This patient exhibited improved detection of targets in his left visual field when his left arm was extended and placed near the target stimuli (Schendel and Robertson, 2004). Further support for distinct contributions of both the effector and the movement goal on visual selection has been obtained in evoked-response studies (Forster and Eimer, 2007; Gherri et al., 2007). Forster and Eimer (2007) cued participants to prepare movements of one hand (the effector) directed to touch the index finger of the opposite hand (the goal). Tactile probes were presented to the effector or the goal hand during movement preparation. Somatosensory ERPs to these tactile probes were larger when probes were presented to the effector than when presented to the goal hand, suggesting that attentional engagement was stronger for the effector than for the movement goal. Together, these studies suggest that proprioceptive signals guide attention toward locations *near* the hand which may facilitate the interaction with objects. This notion gains support from physiological recording in non-human primates which found visuo-tactile neurons that respond to the combined visual and somatosensory feedback from the body (Graziano and Gross, 1998; see also Andersen et al., 1997, for a review).

The studies reviewed so far have generally segmented the normally continuous stream of movement into discrete units of analysis. In other words, the focus has been on static hand postures or single actions. This convenience-driven methodological practice limits our knowledge about attention deployment during continuous movements in more realistic tasks, such as manipulating hand-held devices. Recently, a few studies have re-examined the online influence of action on perception (for recent reviews, see Tseng et al., 2012; Brockmole et al., 2013). One such example is Adam et al. (2012), who studied the effect of hand proximity on letter identification performance while participants adopted a bimanual posture (static) or performed a movement (dynamic) underneath a display. Results confirmed and extended earlier findings of improved probe identification near the hand (the "near-hand effect") to bimanual continuous movements. In contrast to this result, using a single hand movement, letter discrimination was best when the hand was far from and moved toward the probe (a "far-hand effect"; Festman et al., 2013). Both studies converge on the view that proprioceptive information regarding the current hand position can affect the distribution of spatial attention during the execution of hand movements. However, it remains unclear how the near-hand effect and the far-hand effect together influence visual selection during continuously changing hand movements.

To examine the interplay of near- and far-hand effects, we combined visually concealed continuous hand movements (Adam et al., 2012; Festman et al., 2013) with an attentionally demanding letter discrimination task (Braun and Julesz, 1998) that was presented contingent upon the course of hand motion. Our participants were required to move their (concealed) right hand back and forth, from side to side, under a display, while their static (visible) left hand was next to a keyboard to the left of the display. During the hand movement, a brief visual probe stimulus appeared contingent upon the right hand passing through one of six positions. In this experimental design both the near- and the far-hand effect are likely to modulate visual selection. We hypothesized that if the near-hand effect (hand proximity) is dominated by static hand posture, it will facilitate selection to the left side of the display (i.e., improve performance for attentional probes presented left of fixation). In contrast to that, if the far-hand is driven by dynamic hand motion, as revealed in our recent study (Festman et al., 2013), it will facilitate or attenuate selection depending on movement direction. If selection in the left side of the display is facilitated by the nearby presence of the left hand, the far-hand effect should have an impact mainly on the right side of the display (i.e., modulating performance for attentional probes presented to the right of fixation).

METHODS

PARTICIPANTS

A convenience sample of five participants (age: 20–27, 2 male, all right handed) with normal or corrected-to-normal vision participated in the experiment. They gave written informed consent and were paid for their participation.

APPARATUS

Participants were seated in front of a two-layered computer-desk. Their left hand was placed near the lower right side of a keyboard placed left of display. Their right hand was placed on the shelf below a 22 inch LCD screen (65 × 41° usable field of view), which was set on the top layer of the desk, with an angle of 30° to the horizon (see **Figure 1A**). When viewing the screen from above (viewing distance 35 cm), the right hand was invisible to the participants. Hand position was monitored via a single-button Apple optical computer mouse that was held by the right hand and allowed hand-position contingent probe onsets. Mouse speed was matched to that of hand speed, so that the cursor position (hidden from observers) was always contingent with hand position. Mouse acceleration was disabled. The keyboard was used for recording participants' responses with their left hand.

STIMULI

The experiment was programed and controlled in Matlab. All stimuli were generated by using the Psychophysical Toolbox (Brainard, 1997; Pelli, 1997). The attentional probe was a rotated T or L (size: 2.4 × 2.4°, eccentricity: 10.3°) that was presented either to the left (L) or to the right (R) of a fixation cross (size: 2 × 2°) that was shown continuously 6° below the display center (position C). After an individually adjusted stimulus onset asynchrony (SOA) the probe was followed by an F-shaped mask at the same location (**Figure 1B**).

PROCEDURE

On every trial, participants were required to move their hand once from the right side to the left side under the computer screen and back (thus covering a distance of 45 cm twice). Before each movement, two short audio tones (1200 Hz) were played with an interval of 1200 ms, used for both cuing participants to initiate the hand movement and indicating the time from the start to the reverse of the movement, thus prescribing a movement speed of 37.5 cm/s.

During the hand movement, the visual probe was presented briefly, followed by a mask. In order to prevent a direct fixation on the probe, we used short SOAs (typically <150 ms) that were individually adjusted through an adaptive staircase procedure. On each trial, the probe was displayed either in the lower left or in the lower right location of the screen with one of six equiprobable onset times: The probe appeared either with the hand reaching position R, C, or L while moving to the left side of the screen or with the hand reaching position L, C, or R while moving back toward the starting position under the right edge of the screen (**Figure 1B**). After movement completion, participants indicated the probe's identity via a keyboard press with their left hand. Pretests established that onset delays were minimized to one frame and this was the same in all conditions. If a larger delay occurred, this was registered and the trial was discarded.

There were a total of 24 different trial conditions (2 probe positions × 2 letter probes × 6 hand positions). Each block consisted of 30 trials: 24 trials with probe presentation (1trial per condition) and 6 additional trials without probes. This paradigm enables the examination of the influence of both hand proximity (near-hand effect) and hand movement direction (movement direction effect) on the allocation of covert attention.

Participants were trained for at least 1–2 h on performing the hand motion and probe discrimination task before data collection. Participants started with an SOA value of 250 ms that was either decreased or increased by 50 ms if performance in the previous block exceeded 85% correct discriminations or undercut 65% correct discriminations, respectively. The training ended when participants performed probe identification at 75% correct with SOA values <200 ms. However, since participants' performance could further improve, this staircase procedure continued during testing. Each participant was tested for 3–5 h each, on separate days over a period of 1–2 weeks. This resulted in 900–1200 trials per participant.

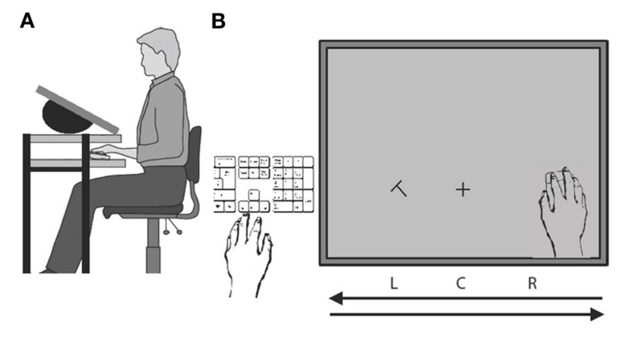

FIGURE 1 | Schematic illustration of the experimental setup. (A) Side view. **(B)** Bird's eye view of the two hands and their respective tasks. The right hand was always moving from right to left and back on a shelf under the display. Participants discriminated a probe letter (T or L) that was briefly displayed to the left or right of a fixation cross and was followed by an F-shape mask (not illustrated). Probes were displayed when the right hand reached positions R, C, or L during either leftward or rightwards movement. After motion completion the participant indicated the probe's identity by keyboard press with the visible left hand.

RESULTS

Data were filtered as follows; experimental trials with movement times <1.4 or >3.0 s or with SOAs >220 ms were excluded to ensure homogeneity of performance and to prevent contamination from probe-directed eye movements (2% of all the data). Average movement time was 2.311 s ($SD = 0.083$), and average SOA was 137 ms ($SD = 18$). Mean probe discrimination performance across participants as a function of the time course of hand position (along the x-axis) is shown in **Figure 2**, separately for the two probe locations.

The data were analyzed separately for left and right probe locations because this factor did not interact with any other factor in a 3-Way ANOVA (this was also the case in the previous published study with a larger sample size, see Festman et al., 2013). Given our prediction of a selective effect of hand placement, separate repeated measure analyses of variance (ANOVA) were conducted for the two probe locations (left and right side of the display) on the mean performance in probe discrimination, with hand position (six levels) as within-subjects variable. We found that when the probe was presented to the right of fixation, there was a significant effect on hand position on discrimination performance [$F_{(5,\ 20)} = 3.704$, $p < 0.05$; see **Figure 2** open circles] ($M = 77.5$, 78.8, and 72.3% for the R, C, and L positions, correspondingly, when participants moved their hand leftward and 82.6, 81.8, and 82.1% for L, C, and R positions, correspondingly, when they moved their hand rightward during the latter part of the motion course). However, when the probe was presented to the left of fixation, there was no effect of hand position during the movement on discrimination performance [$F_{(5,\ 20)} = 0.339$, $p > 0.75$; see **Figure 2** full circles].

The main effect of right hand position did not reach significance [$F_{(2,\ 8)} = 0.685$]. We found a trend for the interaction of hand position and probe location; When participants' hand was

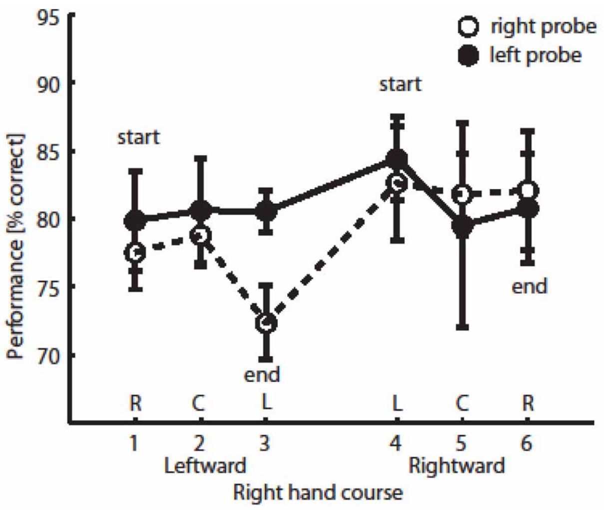

FIGURE 2 | Probe discrimination performance. Performance on trials with right probe location (open circles) or left probe location (full circles), depending on hand position (x-axis, proportional to time on trial). Each circle denotes average performance (with SE).

under the left side of the display (position L), mean performance was higher in trials with left probe compared to trials with right probe [82.5 vs. 77.5%, $F_{(2,\ 8)} = 4.056$, $p = 0.11$; see **Figure 3B**].

The participants were instructed to perform two continuous smooth hand movements from side to side in every trial. The turning point under the left edge of the screen was therefore an endpoint of leftward movement and a start point of rightward movement, just as the point under the right edge of the screen served as a start point for leftward movements and end point for rightward movements. A 2-factor repeated measures analysis of variance (ANOVA) was conducted to evaluate effects of movement latency (start, intermediate, end) and movement direction (leftward, rightward) on perceptual performance. Neither the main effects nor the interaction reached significance [$F_{(2,\ 8)} < 1$], suggesting that the turning point does not induce an effect on attentional allocation.

Trials were then classified with regard to the proximity between probe location and hand proximity (near, intermediate, and far) and with regard to the direction of hand movement relative to the probe position (i.e., leftward hand movements were defined as movement *toward* the left probe and *away* from the right probe, and vice versa for rightward hand movements; see **Figure 3A**). Separate 2-factors repeated measure analyses of variance (ANOVA) were conducted for the two probe locations on the mean performance in probe discrimination, with hand proximity (three levels) and movement direction (two levels) as within-subjects variables. We found a significant interaction of hand proximity and movement direction when the probe was presented to the right of fixation; mean performance was significantly higher when the participants' hand was under the left side of the display (far proximity) moving toward it (rightwards), compared to when moving away from it (leftwards) [82.6 vs. 72.3%, $F_{(2,\ 8)} = 4.494$, $p < 0.05$, see **Figure 3D**]. No significant effect of movement direction was found in trials with left probe [$F_{(1,\ 4)} = 0.348$, see **Figure 3C**].

DISCUSSION

The present study examined the combined effect of a static (left) hand and dynamic (right) hand on visual discrimination performance. Our findings revealed a strong modulation in performance by the direction of hand movement which is strongest when the moving hand is far from the attentional probe and moving toward it (replicating the "far-hand effect"; Festman et al., 2013). However, probes presented to the left of fixation were not affected by this far-hand effect, suggesting that the nearby (static) presence of the left hand eliminated the far-hand effect for left side probes.

The present result helps to clarify the apparent difference between the "near-hand effect" of Adam et al. (2012) and the "far-hand effect" of Festman et al. (2013). Specifically, the bimanual counterpace movement task of Adam et al. brought one hand in the vicinity of the other hand as the two hands moved together, thus shrinking the size of the attentional pragmatic map. In contrast, participants in Festman et al.'s earlier study used only a single hand, thus allowing for a shift of the entire pragmatic map toward far probe locations, which enhanced visual selectivity

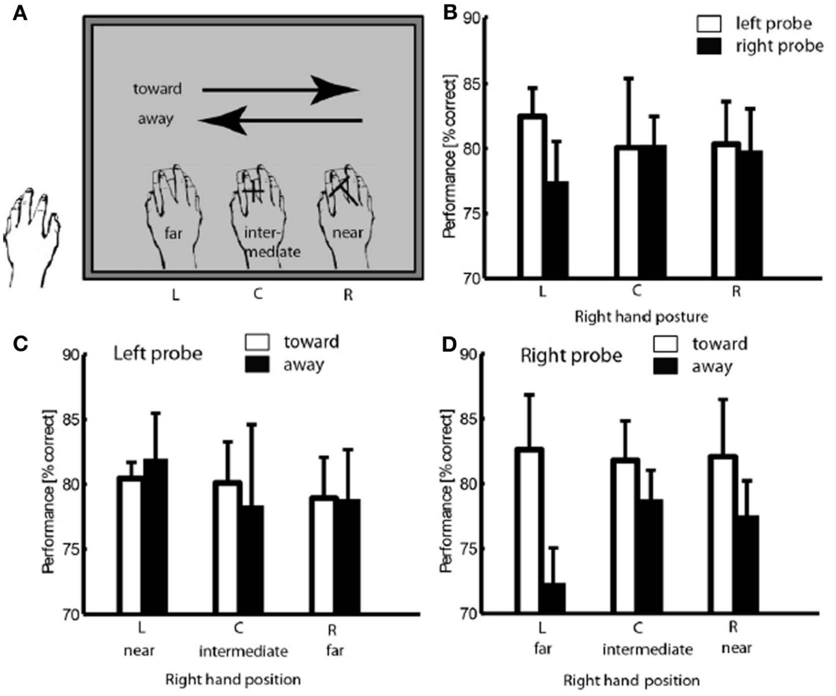

FIGURE 3 | Illustration of trial classification, using a trial with probe at position R as example (A). Performance in different hand positions for two probe locations. **(B)** Performance in discrimination left and right probe as a function of hand position and movement direction **(C,D)** Error bars show standard error of the mean.

there. The present study, by simply placing observers' other hand near the turning point of the hand movement, reduced the resulting far-hand effect again, therefore suggesting that attentional pragmatic maps are dynamically delimited by the current positioning of both hands, as was proposed by Rizzolatti et al. (1994).

Recently it has been suggested that visual processing is altered near the hands. Gozli et al. (2012) found that placing the hands near the display improves performance in temporal tasks, while attenuating performance in spatial tasks. In the current study, the letter discrimination task demands both spatial and temporal detection. Hand movements toward or away from the probe letter appear to facilitate or attenuate visual processing, respectively. However, the nature of the task we employed does not reveal whether magno- or parvo-cellular processing is affected.

Our initial result does not clarify whether the modulating effect of the left hand is driven by its visual or proprioceptive cues. While future work should investigate this point, we refer readers to the work of Reed et al. (2006, Experiments 2 and 3) which suggests that hand proprioception is sufficient to modulate visuo-spatial attention near the hand.

Our findings are consistent with a bimodal neuronal integration mechanism that processes both visual information and motor feedback (efference copy signals) from the body (Graziano and Gross, 1998). This, in turn, provides an online, multisensory representation of visual information in peri-personal space centered on active body parts (see Graziano and Gross, 1998; Graziano, 2001) and is also involved in directing spatial attention (Bremmer et al., 2001; Halligan et al., 2003). This bimodal integration mechanism has been made responsible for earlier findings of a near-hand advantage for visual attention in search, detection, and attentional blink tasks (cf. Abrams et al., 2008). More recently, it has also been proposed to account for the modulating effects of hand position in flanker interference tasks (Davoli and Brockmole, 2012).

To summarize, our movement-contingent attentional probing method is capable of discovering the combined impact of both static and dynamic hand positions on visual attention deployment. Further studies of this proposed mechanism may expand our understanding of information uptake in real-life situations, such as swiping movements and other manual interactions with hand-held devices—for example, smart phones and tablet PCs (Dufau et al., 2011; Miller, 2012).

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Biased attention near another's hand following joint action

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Previous research has shown that attention is prioritized for the space near the hand, leading to faster detection of visual targets appearing close to one's own hand. In the present study, we examined whether observers are also facilitated in detecting targets presented near another's hand by having participants perform a Posner cueing task while sitting next to a friend. Across blocks, either the participant or the friend placed a hand next to one of the target locations. Our results robustly showed that participants detected targets appearing near their own hands more quickly than targets appearing away from their hands, replicating previous work demonstrating that spatial attention is prioritized near one's own hand (Experiments 1–4). No such attentional bias effects were found for targets appearing near the friend's hand, suggesting that spatial attention is not automatically prioritized near another's hand (Experiments 1 and 2). However, participants were faster to detect targets near the friend's hand following a joint action task, suggesting a shared body representation plays an influential role in biasing attention to the space near another's hand (Experiment 4).

Keywords: spatial attention, hand position, perihand space, joint action, body schema, body representation

INTRODUCTION

When observers position their hands near a visual display, they experience a variety of changes in visual and cognitive processing such as altered perception (Cosman and Vecera, 2010), memory (Tseng and Bridgeman, 2011), and semantic processing (Davoli et al., 2010). The presence of the hands also influences attentional processing, prolonging visual search (Abrams et al., 2008), delaying switches between processing global vs. local aspects of hierarchical figures (Davoli et al., 2012), and biasing the allocation of spatial attention to locations near the hands (Reed et al., 2006, 2010). In addition, observers suffering from visual neglect experience an attenuation of symptoms when they place a hand in the affected visual field (e.g., di Pellegrino and Frassinetti, 2000). This near-hand attentional facilitation effect may reflect a system of bimodal neurons responding to tactile and visual stimuli presented near the hand that strengthens visual processing of objects in perihand space (Graziano et al., 1997; di Pellegrino and Frassinetti, 2000; Schendel and Robertson, 2004; Reed et al., 2006), prioritizing processing of items near the hand that are candidates for future actions (Abrams et al., 2008; Cosman and Vecera, 2010; Reed et al., 2010; Tseng and Bridgeman, 2011).

Although the recent influx of research investigating vision near the hands clearly demonstrates that observers process and represent objects viewed near their own hands in a specialized manner, little work has examined whether the visual system might also prioritize visual information presented near the hands of another actor. Others' hands hold a special social significance. People often use their hands to direct others' attention through pointing and gesturing, creating a joint focus of attention (e.g., Bangerter, 2004). Observers seem to automatically process deictic gestures, taking in information about the direction of another individual's social attention (Langton et al., 1996; Langton and Bruce, 2000). In addition, when an individual sees another actor perform an action, neurons representing that action become active in the observer's motor cortex (e.g., Gallese et al., 1996). This automatically activated motor representation of the observed action closely corresponds to the representation generated when the observer executes the same action (e.g., Iacoboni et al., 1999). These shared representations of observed and executed actions play an influential role in action recognition, action imitation, and the ability to understand the intentions associated with the actions of others (Decety and Grezes, 1999; Blakemore and Decety, 2001; Rizzolatti et al., 2001; Buccino et al., 2004; Rizzolatti and Craighero, 2004; Iacoboni et al., 2005). In addition, observers employ similar neural mechanisms to monitor their own and others' task performance (van Schie et al., 2004) and integrate the potential acts of others into their own action plans (Sebanz et al., 2003, 2005; Atmaca et al., 2008). When individuals must work together to perform a task, they perceive object affordances based not on their own solo capabilities, but on what they can accomplish with their partner (e.g., Marsh et al., 2006). Observers also represent objects in terms of their affordances even when these objects are outside of their own reaching space, but remain in the reaching space of another actor (Costantini et al., 2011; Cardellicchio et al., 2013). Such findings suggest that observers map space not only in terms of their own action affordances, but also based on the potential of others to act on the environment.

Given the importance of others' hands in directing social attention and the significant role that shared representations play in action understanding and execution, it is possible that observers may experience changes in visual processing near the hands of other actors. We investigate whether observers represent the space near another person's hands in the same biased way they represent the space near their own hands. If the visual system prioritizes information presented near the hands of another actor, then observers should show biases in visual processing not only near their own hands, but also near the hands of others.

To test the hypothesis that the presence of another's hands influences visual processing, we asked participants to perform a covert attention task previously employed in an early study on the effects of hand positioning on visual attention (Reed et al., 2006). In the original work, participants detected a peripheral target appearing to the left or right of a central fixation cross after a highly predictive visual cue. In some conditions, participants placed one of their hands next to one of the target locations. Reed et al. (2006) found that, regardless of cue validity, participants were faster to detect targets appearing near their hands than targets appearing away from their hands, suggesting that participants prioritized attention to the space near their own hands. We used the same paradigm, but asked participants to perform this orienting task while sitting next to a friend. Across blocks, either the participant or the friend placed a hand next to one of the target locations. We were interested in whether the presence of another person's hand would facilitate observers' target detection performance in the same manner as their own hand. In Experiment 1, we examined whether spatial attention is prioritized to the space near one's own as well as another person's hand. In Experiment 2, we investigated the influence of visual similarity between one's own and another's hand on the allocation of attention near the hands. In Experiment 3, we explored how observers allocate attention to the space near a fake hand. Finally, in Experiment 4, we examined the influence of a joint action task on attentional prioritization of the space near the hands of another actor. To preview our results, we found that although participants were consistently facilitated in detecting targets appearing near their own hands or a fake hand corresponding to their own, they only showed an attentional bias near their friends' hands following a joint action task. These findings suggest that the presence of hands only influences visual processing when these hands are incorporated into the observer's own body schema.

EXPERIMENT 1

The main purpose of Experiment 1 was to investigate whether participants' target detection performance in a Posner cueing task (Posner et al., 1987) would be affected by the presence of another person's hand. Although previous studies have shown that attention is prioritized for the space near the hand, leading to faster detection of visual targets appearing close to one's own hand (Reed et al., 2006, 2010), it is unclear whether observers would also be facilitated in detecting targets near another person's hand. If observers automatically prioritize the space near another's hand, participants should detect targets more quickly when they appear near another person's hand than when they appear away from another's hand. However, if the mere presence of another's hand does not lead to a default attentional bias, then the positioning of another person's hand should have no influence on target detection performance.

METHOD

Participants

Thirty-four right-handed North Dakota State University undergraduates (18 females; mean age = 19.03 years) participated in the study for course credit. Participants brought a friend of the same sex to the lab to sit next to them during the study. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study. The experimental protocol was approved by the North Dakota State University Institutional Review Board for the protection of human participants in research, and informed consent was obtained from all participants.

Apparatus

All stimuli were drawn in black against a white background on a 19-inch monitor with a refresh rate of 75-Hz and a display resolution of 1024 × 768 pixels. A chin rest was used to maintain a constant viewing distance of 50 cm. Responses were collected through the computer keyboard. When asked to place a hand on the computer screen, participants and their friends rested an elbow on folded towels on the table to minimize the discomfort associated with prolonged extension of the hand and arm. The experiment was programmed in MATLAB, using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

Procedure and design

Participants performed a covert attention task. During the task, they were presented with a central cross (3.4°), flanked by two empty squares (3.4°) located 7.4° to its left and right side. Participants were instructed to fixate the central cross on each trial. After a random delay lasting 1500–3000 ms, one of the peripheral squares was cued by increasing the thickness of its border. The target (a solid black dot; 2.2°) appeared 200 ms later in either the cued (valid trial) or uncued (invalid trial) square. There were also catch trials in which no target appeared in either square after a cue. Within each hand condition in the current study, 70% of the trials were validly cued, 20% of the trials were invalidly cued, and 10% were catch trials. Participants were instructed to press the space bar on the computer keyboard as soon as they detected the presence of the target and to refrain from responding on catch trials. For both valid and invalid trials, the cue and the target remained visible on the screen until the participant responded; for the catch trials, the cue stayed on the screen for 2000 ms and then disappeared. **Figure 1** illustrates the sequence of events in a trial.

During the experiment, participants performed the covert attention task while sitting next to their friends. Participants' friends sat to their right for half of the experiment and to their left for the other half of the experiment in a counterbalanced order. Participants completed three experimental conditions for both positions. When the participant's friend sat on the right, the three experimental conditions were: (a) no hand on the screen, in which participants responded with the left hand and rested the right hand in the lap while the friend rested both hands in the lap; (b) participant's hand on the screen, in which participants responded with the left hand and placed their right hand next to the right square on the screen while the friend rested both hands in the

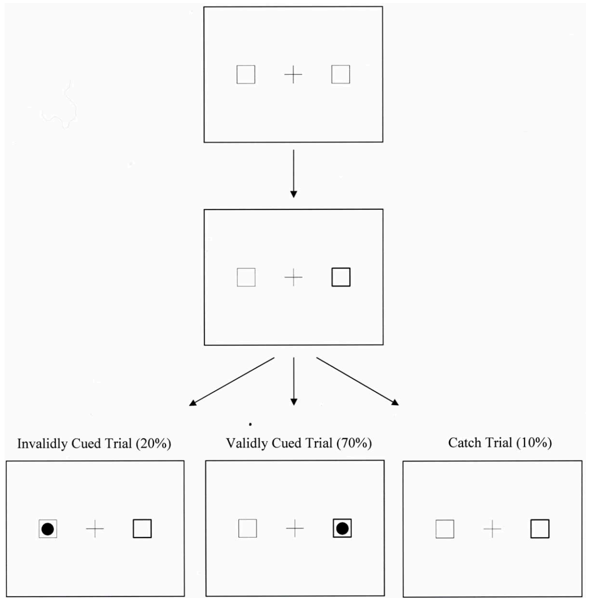

FIGURE 1 | The sequence of events within a trial in Experiments 1–4.

lap; and (c) friend's hand on the screen, in which participants responded with the left hand and rested their right hand in the lap while the friend placed the right hand next to the right square on the screen. When the friend was sitting to the left-hand side of the participants, the three experimental conditions were the same, except that participants responded with their right hand, and participants or their friend placed the left hand next to the left square on the screen when required. For conditions in which a participant or friend placed a hand on the screen, the hand rested next to the outer-edge of the right/left square with the palm facing the square and the tip of the middle finger touching the computer screen. Before a block of trials in these conditions began, participants viewed a display with written instructions about hand placement, the empty squares and central cross, and one small filled dot (0.7°) placed 1.8° to the side of a square that served as a guide to help participants or their friend to position the hand in a consistent location on the display. The guide dot was removed before the first trial in a block began. Before each block of trials in the no hand conditions, participants viewed a display showing written instructions about hand placement as well as the empty boxes and central cross. **Figure 2** shows the experimental settings and hand positions in the different experimental conditions for Experiment 1. There were two blocks of 60 trials for each condition for each friend's sitting position, resulting in a total of 12 total blocks—six blocks in which the friend sat on the participants' left and six blocks in which the friend sat on the participants' right. Block order was randomized. Prior to the formal sessions, participants completed a practice session of 20 trials in the no hand condition.

RESULTS AND DISCUSSION

The dependent measure of interest in the current study was participants' reaction times (RTs) for target detection. Four participants made excessive catch trial response errors (>55%) and were eliminated from analyses. The remaining participants had an overall catch trial error rate of 16%. Data from trials in which participants responded outside a window of 200–1000 ms after the onset of the target (9% of total trials) were also eliminated from analyses to exclude errors of anticipation and inattention.

To examine participants' target detection performance, we conducted a 2 (friend's sitting position: left, right) × 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) × 2 (cue validity: valid, invalid) repeated measures ANOVA. The results showed a significant main effect of the friend's sitting position, $F_{(1\ 29)} = 4.765$, $p = 0.037$, indicating that participants responded faster when their friend sat on their left- compared to right-hand side. This may be due to the fact that when a friend was sitting on participants' left-hand side, participants had to respond with their dominant hand (right hand) and thus produced faster response times[1]. Additionally, there was a significant main effect of cue validity, $F_{(1,\ 29)} = 121.069$, $p < 0.001$, showing that participants responded more quickly to validly compared to invalidly cued trials. Importantly, the three-way interaction between friend's sitting position, hand position, and target side was also significant, $F_{(2,\ 58)} = 10.166$, $p < 0.001$. There were no other significant main effects or interactions. As in previous research employing this paradigm, cue validity had no impact on near-hand effects, suggesting that hand presence did not influence the shifting of attention, but instead affected attentional prioritization of space (Reed et al., 2006, 2010). **Figure 3** shows the mean reaction times across all participants in the different experimental conditions collapsed across cue validity.

Separate 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) ANOVAs were conducted for each sitting position to further examine the three-way interaction effect. The results showed that when a friend sat on the left-hand side of the participants, there were no significant main effects of hand position, $F_{(2,58)} = 1.566$, $p = 0.218$, or target side, $F_{(1,\ 29)} = 0.741$, $p = 0.396$. However, the interaction between hand position and target side was significant, $F_{(2,\ 58)} = 3.796$, $p = 0.028$. Paired-samples t-tests further showed that participants were faster to detect targets appearing next to their own hands than targets appearing away from their hands, $t_{(29)} = -2.330$, $p = 0.027$, but were no faster to detect targets on one side of the screen than another when their friend's hand was on the screen $t_{(29)} = -0.410$, $p = 0.685$, or when no hand was placed on the screen, $t_{(29)} = 0.524$, $p = 0.604$. The same results were obtained when a friend sat on

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[1] We also conducted a 2 (friend's sitting position: left, right) × 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) repeated measures ANOVA on catch trial error data that revealed a significant main effect of the friend's sitting position, $F_{(1,\ 29)} = 8.108$, $p = 0.008$, showing that participants made more catch-trial errors when a friend sat on their left-hand side (20%) compared to when a friend sat on their right-hand side (13%). The speed advantage for responses when a friend sat on the left-hand side may therefore also reflect a speed-accuracy trade off. No other main effects or interactions were significant for the error data (all p-values >0.05).

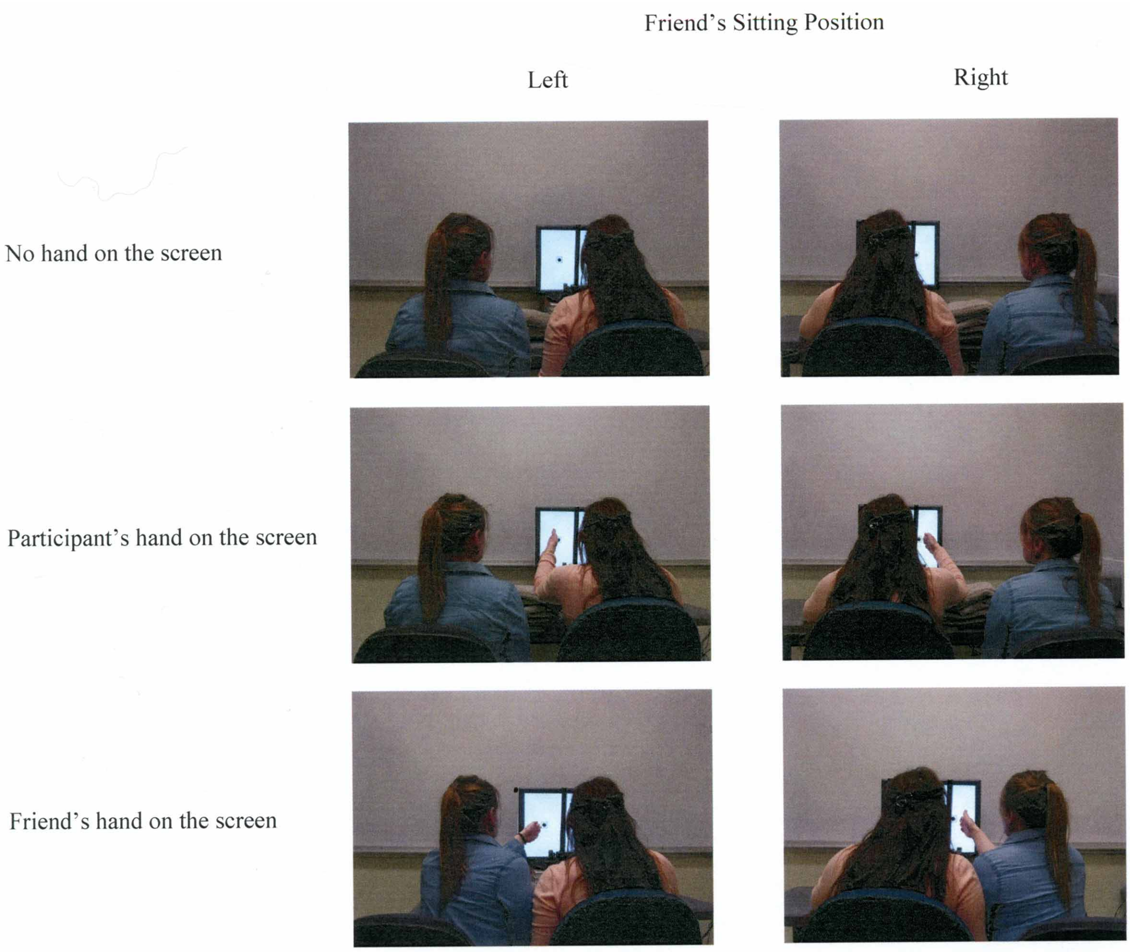

FIGURE 2 | Experimental setup and hand positions in Experiment 1.

the right-hand side of the participants. There were no significant main effects of hand position, $F_{(2,\ 58)} = 1.781$, $p = 0.178$, or target side, $F_{(1,29)} = 1.999$, $p = 0.168$, but the interaction between hand position and target side was significant, $F_{(2,\ 58)} = 4.498$, $p = 0.015$. Paired-samples t-tests showed that participants responded faster to targets appearing next to their hand compared to targets appearing away from their hand, $t_{(29)} = -2.783$, $p = 0.009$, but again, there were no differences between target detection times when a friend's hand was placed on the screen, $t_{(29)} = -1.026$, $p = 0.313$, or when no hand was placed on the screen, $t_{(29)} = 0.643$, $p = 0.525$. Together, these results suggest that target detection was facilitated near participants' own hands, but not their friend's hands.

In sum, Experiment 1 demonstrated that participants' detection performance was better for targets appearing near their own hands compared to targets appearing away from their hands, replicating previous research showing that the presence of one's own hand affects attentional prioritization and results in faster target detection near the hand (e.g., Reed et al., 2006, 2010). However, the results of Experiment 1 showed that participants were no faster to detect targets near a friend's hand than targets away from a friend's hand. Therefore, although previous research has shown that observers' attention is sensitive to the signals generated by others' hands (e.g., Langton et al., 1996) and that observers represent the actions and affordances of others in the same way they represent their own (e.g., Sebanz et al., 2003; Costantini et al., 2011), our results indicate that observers do not automatically prioritize the space near a friend's hand during a covert attention task. The biases associated with visual processing near the hands may be unique to an observer's own hands.

EXPERIMENT 2

The results of Experiment 1 showed that the mere presence of another's hand is not sufficient to bias participants' attention to the space near a hand that is not their own. These results suggest that only the presence of one's own hands will drive changes in visual processing. Yet previous research suggests that the presence of a fake hand can also alter vision: when participants wear a rubber glove that matches a glove on a fake hand positioned on a display, they are faster to detect targets appearing near the fake hand than targets appearing away from the fake hand (Reed et al., 2006). Presumably, the correspondence between the rubber glove

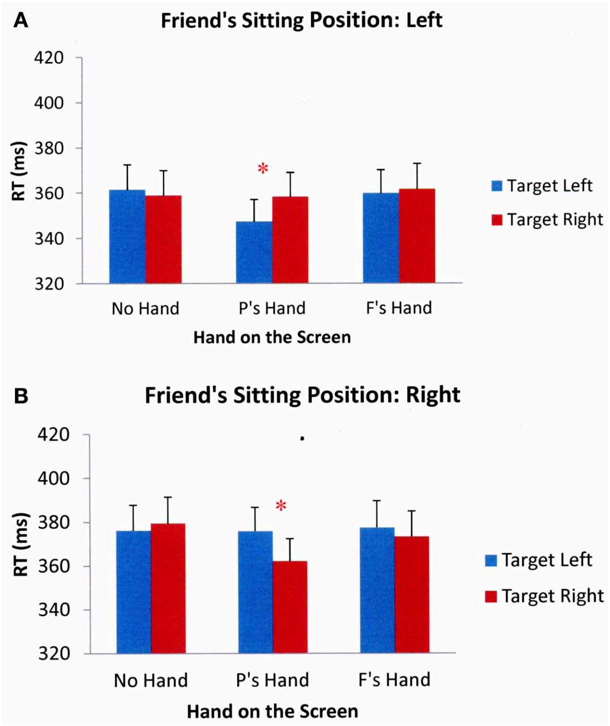

FIGURE 3 | Mean reaction times across all participants in different Experimental conditions of Experiment 1 when a friend was sitting to the participants' left (A) and right (B). Error bars represent standard errors of the means. (Note: P's = Participant's; F's = Friend's). $^*p < 0.05$.

on the false hand and the glove on the participants' own handled participants to prioritize the space near the fake hand. Perhaps observers would likewise prioritize attention near a friend's hand if there were sufficient correspondence between their own and their friends' hands. To examine this possibility, in Experiment 2, we replicated the design of Experiment 1 but increased the visual similarity between the participants' own hands and their friends' hands. Participants and their friends wore matching rubber gloves to increase the correspondence between hands. If the visual similarity between hands creates a correspondence that leads observers to prioritize the space near another's hand, participants should respond faster to targets appearing next to their friend's hand than targets appearing away from the hand.

METHOD

Participants

Thirty-two right-handed undergraduates from North Dakota State University (17 females; mean age = 19.03 years), all with normal or corrected-to-normal vision, participated in the study for course credit with a friend of the same sex. Participants were naïve to the purpose of the study and had not participated in the previous experiment.

Apparatus, procedure, and design

Experiment 2 was identical to Experiment 1, except that we had participants and their friends put a rubber glove on the hand that had to be placed on the screen. That is, when a friend was sitting on the right-hand side of the participants, they had to put a rubber glove on their right hand, and vice versa. Therefore, four rubber gloves were used: two for participants' right and left hands, and two for their friends' right and left hands.

RESULTS AND DISCUSSION

We used the same criteria as in Experiment 1 to analyze participants' RTs to detect the target. Four participants were excluded for excessive catch trial errors. The overall error rate for the remaining participants was 15% and another 8% of trials fell outside the window of 200–1000 ms[2]. The data were submitted to a 2 (friend's sitting position: left, right) × 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) × 2 (cue validity: valid, invalid) repeated measures ANOVA. The results showed a significant main effect of cue validity, $F_{(1,\ 27)} = 144.263$, $p < 0.001$, demonstrating that participants were faster in responding to validly cued targets compared to invalidly cued targets. There was also a significant three-way interaction between friend's sitting position, hand position, and target side, $F_{(2,\ 54)} = 6.825$, $p = 0.002$. There were no other significant main effects or interactions. The mean RTs across participants in different experimental conditions collapsed across cue validity are shown in **Figure 4**.

To further examine the significant interaction between the friend's sitting position, hand position, and target side, separate 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) ANOVAs were then carried out for participants' target detection performance in each sitting position. The results showed that when a friend was sitting to the participants' left, there were no significant main effects of hand position, $F_{(2,\ 54)} = 1.295$, $p = 0.282$, or target side, $F_{(1,\ 27)} = 1.107$, $p = 0.302$. However, the interaction between hand position and target side was significant, $F_{(2,\ 54)} = 3.369$, $p = 0.042$. Subsequent paired sample t-tests showed that, as in Experiment 1, participants were faster when responding to targets appearing next to their own hand compared to targets appearing away from their hand, $t_{(27)} = -2.920$, $p = 0.007$. However, again there were no differences in detecting targets that were presented near and away from a friend's hand, $t_{(27)} = 0.508$, $p = 0.615$, or when no hand was placed on the screen, $t_{(27)} = -0.370$, $p = 0.714$. Similar results were obtained when a friend was sitting to the participants' right. There were no significant main effects of hand position, $F_{(2,\ 54)} = 0.318$, $p = 0.729$, or target side, $F_{(1,\ 27)} = 0.790$, $p = 0.382$. However, the interaction between hand position and target side was significant, $F_{(2,\ 54)} = 4.508$, $p = 0.015$. Paired-samples t-tests showed that participants responded faster to targets appearing next to their hand compared to targets appearing away from their hand, $t_{(27)} = -2.924$, $p = 0.007$. However, this near-hand facilitation effect was absent when a friend's hand was held on the screen, $t_{(27)} = -0.192$, $p = 0.849$, or when no hand was held on the screen, $t_{(27)} = 1.857$, $p = 0.074$. Together,

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[2] An analysis of catch trial errors revealed no significant main effects or interactions between the factors of friend's sitting position and hand position (all p-values >0.05).

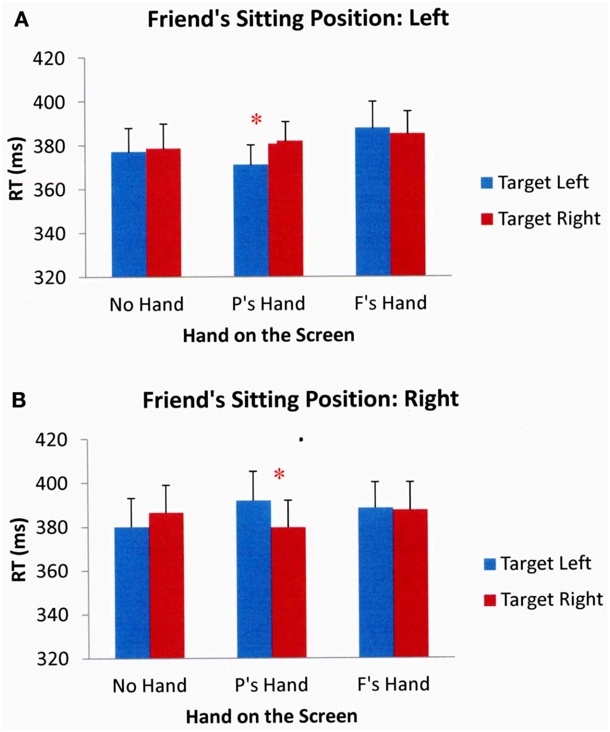

FIGURE 4 | Mean reaction times across all participants in different Experimental conditions of Experiment 2 when a friend was sitting to the participants' left (A) and right (B). Error bars represent standard errors of the means. (Note: P's = Participant's; F's = Friend's). $*p < 0.05$.

these results suggest that even under conditions in which visual similarity between hands was high, target detection performance was affected by the proximity of one's own but not another's hand.

The results of Experiment 2 again showed that participants responded more quickly to targets appearing near their own hands compared to targets appearing away from their hands, demonstrating the robustness of the attentional bias effect near one's own hand. However, there was no such facilitation effect when comparing the conditions in which participants had to detect targets appearing near or away from their friend's hand. Although we increased the visual similarity between participants' hands and the hands of their friends, the presence of a friend's hand on the screen had no influence on participants' reaction times to detect targets. While visual similarity between an observer's own hand and a fake hand may lead observers to prioritize the space near a fake hand (Reed et al., 2006), the same visual similarity was not sufficient to change visual processing near the hands of another person. Instead, the results of Experiment 2 again point to the conclusion that observers do not prioritize the space near a friend's hand, even when this hand looks like their own.

EXPERIMENT 3

Although Reed et al. (2006) showed that attention is biased to the space near a fake hand when observers wear a rubber glove that matches this false hand, the results of Experiment 2 show that using a similar technique to increase visual similarity between the hands of two people is not sufficient to make observers prioritize the space near the hand of another person. Why would participants show an attentional bias near a fake hand made to look like their own, but disregard the hands of another person that also shared their appearance? One possibility that may explain this discrepancy is that the visual system might not represent a fake hand and a real person's hand in the same way. That is, when observers know they are viewing a hand that belongs to another person, they may treat this hand differently than a hand that looks the same but cannot possibly belong to anyone else. Participants in Reed et al.'s (2006) study who prioritized the space near a fake hand may have incorporated the fake hand into their body schema through the simultaneous tactile sensation of the rubber glove on their own hand combined with the visual signal of the rubber glove on the fake hand. Visual information from a rubber hand that corresponds to an observer's unseen real hand can be sufficient to shift the receptive fields of multisensory neurons (Graziano, 1999; Graziano et al., 2000) and create crossmodal congruency effects (Pavani et al., 2000). In Experiment 3, we examine the idea that a fake hand that is visually similar to an observer's real hand is sufficient to bias attention. We designed this experiment as a replication of Reed et al. (2006) Experiment 4. If participants incorporate a realistic-looking fake hand into their own body schema, then they should show faster detection of targets appearing next to this fake hand.

METHOD

Participants

Forty-three right-handed North Dakota State University undergraduates (17 females; mean age = 19.50 years) participated in the study for course credit. All had normal or corrected-to-normal vision, and none of them had participated in the previous experiments.

Apparatus, procedure, and design

Experiment 3 was identical to Experiment 2, with the exception that participants were not required to bring a friend to the study; instead, two fake hands were used to replace a friend's left and right hand. As in Experiment 2, when a fake hand was placed on the participants' left, participants had to put a rubber glove on their left hand, and vice versa. The fake hands were made by stuffing rubber gloves with a water bottle and cotton. When a fake hand was placed next to a square on the screen, it was supported by boxes and folded towels on the table. **Figure 5** shows the experimental settings and hand positions in the different experimental conditions for Experiment 3.

RESULTS AND DISCUSSION

Participants' target detection performance was analyzed according to the same criteria as in the previous experiments. Five of the participants were eliminated due to excessive errors on the catch trials. The overall error rate for the remaining

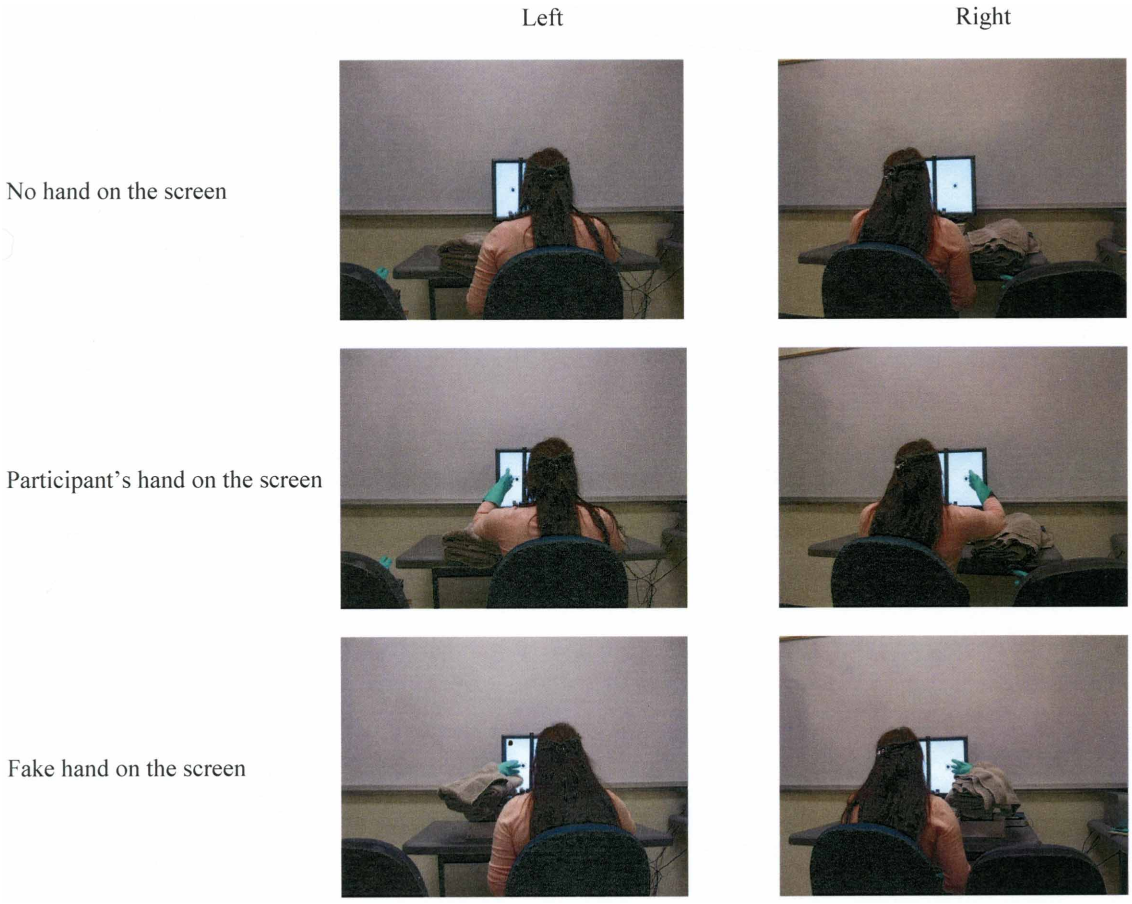

FIGURE 5 | Experimental setup and hand positions in Experiment 3.

participants was 13%[3]. Additionally, data from trials in which participants responded outside the 200–1000 ms window (6% of total trials) were eliminated from analyses. As before, the results of a 2 (fake hand's position: left, right) × 3 (hand position: no hand on the screen, participant's hand on the screen, fake hand on the screen) × 2 (target side: left, right) × 2 (cue validity: valid, invalid) repeated measures ANOVA showed a significant main effect of cue validity, $F_{(1,\ 37)} = 171.178$, $p < 0.001$, suggesting that participants responded faster to validly cued targets than to invalidly cued targets. There was also a significant interaction between the fake hand's position and target side, $F_{(1,\ 37)} = 21.513$, $p < 0.001$, and this interaction was affected by hand position, $F_{(2,\ 74)} = 7.528$, $p = 0.001$. There were no other significant main effects or interactions. The mean RTs across participants in different experimental conditions collapsed across cue validity are shown in **Figure 6**.

To further examine the significant three-way interaction between the fake hand's position, hand position, and target side, separate 3 (hand position: no hand on the screen, participant's hand on the screen, fake hand on the screen) × 2 (target side: left, right) ANOVAs were performed on participants' target detection performance when a fake hand was positioned on either the left- or right-hand side of the participants. The results showed that when a fake hand was on the participants' left, the main effect of hand position was not significant, $F_{(2,\ 74)} = 0.347$, $p = 0.708$, but there was a significant main effect of target side, $F_{(1,\ 37)} = 5.690$, $p = 0.022$. The interaction between hand position and target side was also significant, $F_{(2,\ 74)} = 3.631$, $p = 0.031$. Subsequent paired sample t-tests showed that participants were faster when responding to targets appearing next to their hand compared to targets appearing away from their hand, $t_{(37)} = -2.404$, $p = 0.021$. Participants were also faster when responding to targets that appeared next to the fake hand than to targets that appeared away from the fake hand, $t_{(37)} = -2.642$, $p = 0.012$. However, there were no performance differences in target detection when no hand was placed on the screen, $t_{(37)} = 0.519$, $p = 0.607$. Similar results were obtained when a fake hand was on participants' right. The main effect of hand position was not significant, $F_{(2,\ 74)} = 2.074$, $p = 0.133$, but there was a significant main effect of target side, $F_{(1,\ 37)} = 14.651$, $p < 0.001$ and the interaction between hand position and target side was

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[3] An analysis of catch trial errors showed no significant main effects or interactions (all p-values >0.05) between friend's sitting position and hand position, indicating no systematic effects of these factors on errors.

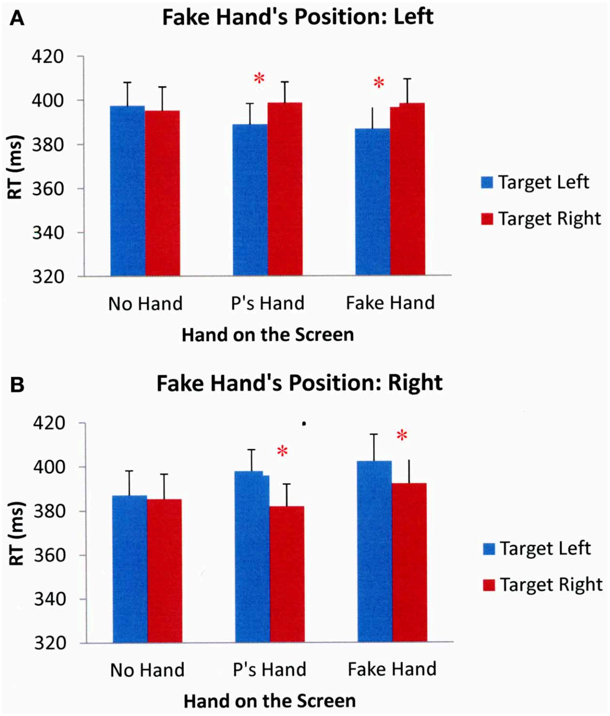

FIGURE 6 | Mean reaction times across all participants in different Experimental conditions of Experiment 3 when a fake hand was positioned on the participant's left (A) and right (B). Error bars represent standard errors of the means. (Note: P's = Participant's). $^*p < 0.05$.

also significant, $F_{(2,\ 74)} = 3.269$, $p = 0.044$. Paired-sample t-tests showed that participants had faster RTs to targets that appeared near their hand than to targets that appeared away from their hand, $t_{(37)} = -3.912$, $p < 0.001$. Participants also responded faster to targets that appeared next to the fake hand compared to targets that appeared away from the fake hand, $t_{(37)} = -2.928$, $p = 0.006$. There were no differences in target detection times when no hand was held on the screen, $t_{(37)} = 0.409$, $p = 0.685$. Together, the results suggest that visual attention can be biased by the proximity of one's own hand as well as a visually similar fake hand.

Participants in Experiment 3 were faster to respond to targets appearing near a fake hand compared to targets appearing away from a fake hand, replicating previous research (Reed et al., 2006) showing that observers prioritize the space near not only their own hands, but also fake hands. These results suggest that people may prioritize the space near a fake hand because they represent the fake hand in multisensory areas. Visual information about hand position provided by a fake hand is sufficient to facilitate responses to objects appearing near the hand. However, although the visual information available to participants in the friend's hand conditions of Experiment 2 was quite similar to the visual information available in the fake hand conditions of the current experiment, the results of Experiment 2 suggest that the visual system treats a real person's hand differently than a fake rubber hand, showing no attentional bias to the real person's hand. Participants may have more readily incorporated a fake hand into their own body schema than their friends' hands: although some evidence suggests that observers incorporate fake hands into their own body schema in the absence of synchronous feedback between visual signals and tactile sensations (e.g., Pavani et al., 2000; Durgin et al., 2007), experiences of confusing another person's hand for one's own typically involve direct synchrony between what observers see and feel (Tsakiris et al., 2005; Schütz-Bosbach et al., 2006), more synchrony than was provided by the conditions of Experiment 2.

The results of the first three experiments suggest that observers may only experience altered vision near the hands when they have incorporated these hands into their own body schema. In Experiments 1 and 2, when participants' friends sat passively throughout the entire experiment, never performing any actions that were relevant to the participants' task, participants showed no visual biases associated with the presence of their friends' hands on the display. The friends were distinctly separate from the participants and the task they were asked to perform.

However, previous studies have shown that external objects can be integrated into one's own body schema after a short period of tool-use training (e.g., Iriki et al., 1996; Maravita et al., 2002; Maravita and Iriki, 2004; Cardinali et al., 2009) and that such tool use can also drive changes in visual processing (e.g., Tseng et al., 2012; Brockmole et al., 2013). Recent findings also suggest that when two people work together on a task, they likewise incorporate representations of their partner's task-relevant body parts into a joint body-schema (Soliman et al., 2012, in preparation). If this is the case, then we predict that attention should be facilitated by the presence of another's hand after participants perform a cooperative task which can enhance the incorporation of another's body parts into their own body schemas. We tested this prediction in Experiment 4.

EXPERIMENT 4

The results of Experiments 1–3 showed that participants do not by default prioritize the space near their friend's hand for attention. Here we investigate the hypothesis that observers will show a bias for the space near another person's hands when they first work together on a joint action task. This task is designed to induce participants to develop a joint body-schema (Soliman et al., 2012, in preparation), essentially serving the same purpose as tool-use training periods in experiments showing that actors integrate tools into their body schemas (e.g., Iriki et al., 1996). In the task, we asked participants and their friends to each hold the end of a wire in one hand and to work together to saw through a wax block using this wire. Following this "training" period, participants again performed the covert-orienting task. If a shared body representation plays an influential role in biasing attention to another's hand, then participants should show better detection performance when the target appears near their own hand as well as near another person's hand after the joint wax-sawing task. However, if a shared body representation is not sufficient for participants to prioritize the space near another's hand for attention, then they should show faster target detection when the targets are presented near their own but not another's hand after the joint wax-sawing task.

METHOD

Participants

Thirty-five right-handed North Dakota State University undergraduates (28 females; mean age = 19.43 years) participated in the study for course credit with a same-sex friend. All had normal or corrected-to-normal vision and had not participated in the previous experiments.

Apparatus, procedure, and design

Experiment 4 was identical to Experiment 1, with the exception that participants and their friends had to perform a joint wax-sawing task for 4 min before the Posner cueing task for each friend's sitting position. Participants and their friends were asked to use a wire to saw a wax block that was held in a holder attached to a table (cf. Soliman et al., 2012, in preparation). The participant held the end of a wire in one hand while the friend held the other end of the wire in the opposite hand. To complete this task, both parties had to coordinate their actions; as participants pulled the wire toward themselves, their friends had to push the wire away from themselves and vice-versa. For the condition in which a friend's sitting position was on the left, the wax-sawing task was performed while the friend stood on the left side of the wax holder using the left hand to saw and the participant stood on the right using the right hand to saw. For the condition in which a friend's sitting position was on the right, participants and their friends switched positions and hands for the wax-sawing task such that the hand the friend used to saw was also the hand they would place on the display. Wax blocks were replaced as needed to keep participants sawing for 4 min. **Figure 7** shows the experimental setup for the joint wax-sawing task.

RESULTS AND DISCUSSION

Participants' target detection performance was analyzed according to the same criteria as in the previous experiments. Two participants were excluded due to excessive errors on the catch trials. For the remaining participants, the overall error rate on catch trials was 11%[4]. Additionally, 5% of the total trials were eliminated for falling outside the 200–1000 ms response window.

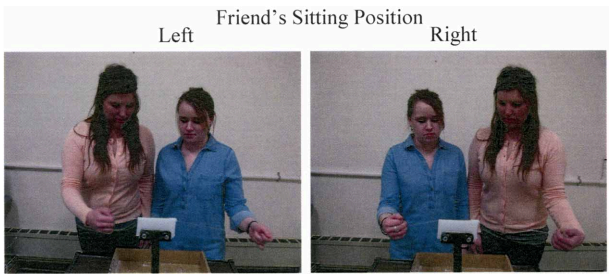

FIGURE 7 | Experimental setup for the joint wax-sawing task prior to the Posner cueing task in Experiment 4.

As before, the results of a 2 (friend's sitting position: left, right) × 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) × 2 (cue validity: valid, invalid) repeated measures ANOVA showed a significant main effect of cue validity, $F_{(1,\,32)} = 122.364$, $p < 0.001$, showing that participants responded faster to validly cued targets than to invalidly cued targets. There was also a significant interaction between friend's sitting position and hand position, $F_{(2,\,64)} = 3.563$, $p = 0.034$, as well as a significant interaction between friend's sitting position and target side, $F_{(1,\,32)} = 22.494$, $p < 0.001$. The interaction between hand position and target side was also significant, $F_{(2,64)} = 3.324$, $p = 0.042$. More importantly, the interaction between friend's sitting position, hand position, and target side was also significant, $F_{(2,\,64)} = 9.434$, $p < 0.001$. There were no other significant main effects or interactions. **Figure 8** shows the mean RTs across participants in different experimental conditions collapsed across cue validity.

To further examine the significant three-way interaction between friend's sitting position, hand position, and target side, separate 3 (hand position: no hand on the screen, participant's hand on the screen, friend's hand on the screen) × 2 (target side: left, right) ANOVAs were performed for each friend's sitting position. When a friend was sitting to the left-hand side of the participant, the results showed significant main effects of hand position, $F_{(2,\,64)} = 3.783$, $p = 0.028$, and target side, $F_{(1,32)} =$

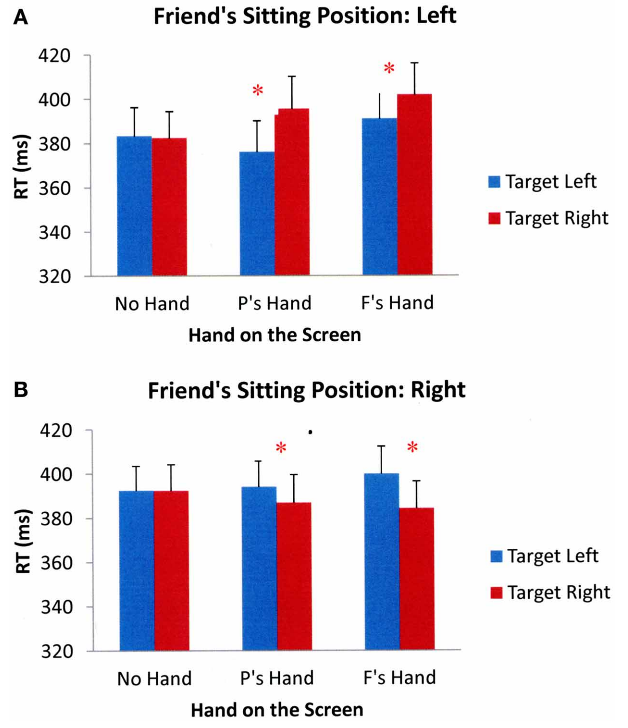

FIGURE 8 | Mean reaction times across all participants in different Experimental conditions of Experiment 4 when a friend was sitting to the participant's left (A) and right (B). Error bars represent standard errors of the means. (Note: P's = Participant's; F's = Friend's). $^*p < 0.05$.

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[4] As in the previous experiments, an ANOVA on catch trial errors with factors of friend's sitting position and hand position showed no significant main effects or interactions (all p-values >0.05), indicating no systematic effects of these factors on catch trial errors.

11.477, $p = 0.002$. However, the interaction between hand position and target side was also significant, $F_{(2,\ 64)} = 7.652$, $p = 0.001$. Subsequent paired sample t-tests showed that participants were faster when responding to targets appearing next to their hand compared to targets appearing away from their hand, $t_{(32)} = -4.096$, $p < 0.001$. Additionally, participants were faster when responding to targets that appeared next to their friend's hand than to targets that appeared away from their friend's hand, $t_{(32)} = -2.696$, $p = 0.011$. There were no performance differences in target detection when no hand was placed on the screen, $t_{(32)} = 0.277$, $p = 0.783$. When a friend was sitting on the right-hand side of the participants, the results showed no effect of hand position, $F_{(2,\ 64)} = 0.108$, $p = 0.897$, but the main effect of target side was significant, $F_{(1,\ 32)} = 6.310$, $p = 0.017$. The interaction between hand position and target side was also significant, $F_{(2,\ 64)} = 5.192$, $p = 0.008$. Paired-samples t-tests showed that participants had faster RTs to targets that appeared near their hand than to targets that appeared away from their hand, $t_{(32)} = -2.040$, $p = 0.050$. Participants also responded faster to targets that appeared next to a friend's hand compared to targets that appeared away from a friend's hand, $t_{(32)} = -4.114$, $p < 0.001$. There were no differences in target detection times when no hand was held on the screen, $t_{(32)} = 0.018$, $p = 0.985$. Together, the results suggest that visual attention can be biased both by the proximity of participants' own hands and their friends' hands after performing a joint action task. When participants have a reason to incorporate a representation of a friend's hands into their own body schema, their visual systems show altered processing near these hands.

GENERAL DISCUSSION

The main purpose of the present study was to investigate how observers allocate attention to visual information presented not only near their own hands, but also near the hands of other actors. Across all four experiments, participants consistently detected targets appearing near their own hands more quickly than targets appearing away from their hands. Additionally, participants in Experiment 3 detected targets more quickly when the targets were presented near a fake hand than when the targets were presented away from a fake hand. The results of Experiments 1 and 2 demonstrate that the mere presence of another's hand was not sufficient to bias attention to the space near this hand: participants in these experiments were no faster to detect targets that appeared close to their friend's hand than targets appearing away from the friend's hand. However, in Experiment 4, after the participants and their friend performed a joint action task together, participants were faster to detect targets appearing near the friend's hand than targets appearing away from the friend's hand.

Across experiments, the present study robustly shows that target detection is faster when targets are presented near participants' hands than when targets are presented away from their hands. These results are consistent with previous work from Reed et al. (2006, 2010), backing up the notion that attention is prioritized for the space near the hand. Objects appearing within perihand space present opportunities for interaction and affect visual processing. This altered vision near the hands may arise via populations of bimodal visuotactile neurons responding exclusively to visual and tactile stimuli presented near or on the hand (Graziano and Gross, 1993, 1998) that strengthen object processing in the space near the hand (e.g., Graziano et al., 1997; di Pellegrino and Frassinetti, 2000; Schendel and Robertson, 2004; Reed et al., 2006, 2010; Abrams et al., 2008; Cosman and Vecera, 2010).

We hypothesized that since observers are sensitive to the signals generated by others' hands (e.g., Langton et al., 1996; Sebanz et al., 2006; Fischer et al., 2008) and experience motor resonance when watching others act (e.g., Rizzolatti and Craighero, 2004), they might also show biases in processing objects presented near the hands of other actors. However, this was not the case in the present study. Our results indicate that observers do not by default prioritize the space near another person's hand. In Experiments 1 and 2, although participants showed a bias toward targets appearing near their own hands, they showed no differences in detecting targets appearing near or away from another's hand. Note that this finding cannot be explained by the lack of proprioceptive information about one's own hand being on the screen: in Experiment 3, even when participants' own hands were in their laps, their attention was biased toward targets appearing near a fake hand. We propose that this facilitation of detection near a fake hand was a result of participants incorporating the fake hand into their own body schema. In other words, participants detected targets that were near the fake hand more quickly because they represented these items as appearing in perihand space.

The results of Experiment 4 further strengthen our inference on the necessity of an observer incorporating a hand into her own body schema in order to experience altered vision near this hand. In Experiment 4, participants' target detection performance was significantly improved for targets appearing near their friend's hand after a joint action task, presumably because the joint action task facilitated the incorporation of another person's hand into one's own body schema. Participants only showed biased attention to the space near their friends' hands after these hands became relevant to accomplishing a shared goal. The results are consistent with a recent study conducted by Soliman et al. (2012, in preparation) showing that after performing a rhythmic sawing task with a partner, participants were slower to localize a vibration applied to their fingers when spatially incongruent visual stimuli (LEDs) were simultaneously observed near the partner's fingers. The researchers attribute the enhanced interference effect to participants incorporating the partner's collaborating hand into their own body representations (Soliman et al., 2012, in preparation). Similarly, we find that participants respond to a visual stimulus appearing near a friend's hand as if it were their own only after engaging in a cooperative task with the friend.

In addition to shedding new light on the question of how the presence of another's hands influences visual processing, our results also add to the growing literature demonstrating the plasticity of body representations. The fact that participants showed biased processing near a friend's hand in Experiment 4 are in line with previous research showing that observers incorporate used tools into the body schema to extend representation of peripersonal space (e.g., Iriki et al., 1996; Maravita et al., 2002; Maravita and Iriki, 2004; Cardinali et al., 2009, 2012). Our findings also compliment those of Reed et al. (2010) in which participants were faster to detect targets appearing near the prongs of a small rake following practice using this tool and research showing that observed tool use can affect perception (Bloesch et al., 2012). Taken together, our results, along with the many others mentioned above, suggest that the representation of one's own body is flexible and that external objects such as tools or even the hands of another actor may be incorporated into one's own body schema following relevant practice or training. These findings also lend support to the notion that changes in visual processing near the hands and the ends of tools are driven by bimodal neurons (Reed et al., 2006, 2010): observers only seem to prioritize the space near a hand or tool when it has been incorporated into the body schema and presumably receives representation in multisensory areas of the brain.

In conclusion, the present study further solidifies the claim that observers prioritize the space near their own hands. In addition, we find that observers do not by default experience changes in visual processing near the hands of other people. However, following a cooperative joint action task, participants show a bias for detecting targets not only near their own hands, but also near the hands of the other actor. These findings suggest that shared body representations may play a crucial role in generating visual biases near the hands of other actors.

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Global and local processing near the left and right hands

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Visual targets can be processed more quickly and reliably when a hand is placed near the target. Both unimodal and bimodal representations of hands are largely lateralized to the contralateral hemisphere, and since each hemisphere demonstrates specialized cognitive processing, it is possible that targets appearing near the left hand may be processed differently than targets appearing near the right hand. The purpose of this study was to determine whether visual processing near the left and right hands interacts with hemispheric specialization. We presented hierarchical-letter stimuli (e.g., small characters used as local elements to compose large characters at the global level) near the left or right hands separately and instructed participants to discriminate the presence of target letters (X and O) from non-target letters (T and U) at either the global or local levels as quickly as possible. Targets appeared at either the global or local level of the display, at both levels, or were absent from the display; participants made foot-press responses. When discriminating target presence at the global level, participants responded more quickly to stimuli presented near the left hand than near either the right hand or in the no-hand condition. Hand presence did not influence target discrimination at the local level. Our interpretation is that left-hand presence may help participants discriminate global information, a right hemisphere (RH) process, and that the left hand may influence visual processing in a way that is distinct from the right hand.

Keywords: peripersonal space, multisensory integration, visual processing, hemispheric specialization, laterality

INTRODUCTION

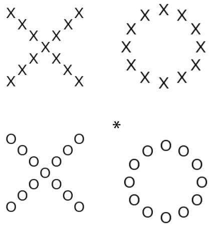
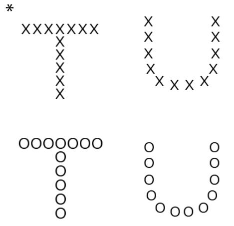
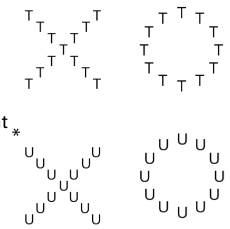
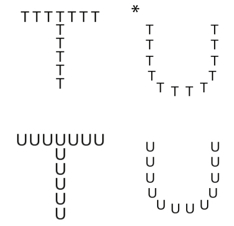
A growing body of work demonstrates that people process visual information differently when stimuli are presented near to rather than far from their hands. Neuropsychological studies, on the whole, indicate that placing a stimulus near one of the hands reduces perceptual and attentional impairments. Visual extinction deficits have been reduced by presenting stimuli near-hand in the contralesional visual field, tactile extinction is exacerbated by presenting a visual stimulus near the ipsilesional hand (Ladavas et al., 1998; di Pellegrino and Frassinetti, 2000), and both detection (Schendel and Robertson, 2004) and discrimination (Brown et al., 2008) benefits have been documented in the defective visual field of cortically-blind patients. Studies of healthy undergraduates have shown that placing a target near one hand has typically led to observations of perceptual facilitation. Placing a hand near a visual target speeds target detection (Reed et al., 2006, 2010; Jackson et al., 2010), causes tactile interference (Spence, 2002), speeds the assignment of figure and ground (Cosman and Vecera, 2010), and leads to greater reaching precision in comparison to responses to targets that appear in the same location but without a nearby hand (Brown et al., 2009). Other studies indicate that people are slower to disengage from visual targets when they appear near the hands (Abrams et al., 2008; Thura et al., 2008; Tseng and Bridgeman, 2011), and that nearby hands slow switching between the global and local levels of a stimulus (Davoli et al., 2012). Evidence suggests that these psychophysical effects are stronger in the presence of the participants' real hand than a fake one (Reed et al., 2006; Brown et al., 2009), while others indicate that near-hand effects can be linked to the presence of an avatar-hand whose movements mirror the actions of the participants' real hand but are not linked to an unmoving avatar (Short and Ward, 2009). Together, this evidence suggests that visual stimuli are processed differently when the observer's own hand(s) is placed near the stimulus rather than when the hand is placed elsewhere.

Compatible explanations for near-hand effects have been offered both at cognitive and neural levels. At the cognitive level, explanations associate hand-presence with the mobilization of additional perceptual (e.g., Cosman and Vecera, 2010) or cognitive processing resources [e.g., attention or working memory (e.g., Reed et al., 2006, 2010; Abrams et al., 2008; Tseng and Bridgeman, 2011; Davoli et al., 2012)]. Cognitive-level accounts are consistent with neural-level accounts in that they both propose that the hands bring additional resources to bear on processing nearby targets. At the neural level, explanations for near-hand effects have focused on findings in the monkey neurophysiology literature showing that 3D visual objects presented in the space near the hands and face recruit visual-tactile bimodal neurons. These neurons have tactile receptive fields (tRFs) on the skin and visual receptive fields (vRFs) that include and extend beyond the tRF into the space surrounding the hand or face. They are activated in response to either tactile or visual stimuli presented on or near the skin (Graziano and Gross, 1993; Graziano et al., 1994; Graziano, 1999; Graziano and Gandhi, 2000; Graziano and Cooke, 2006). These neurons code space near the hand and face more robustly than other body parts, and near-hand space is represented more robustly than space far from the hand (Graziano et al., 1994; Graziano, 1999; Graziano and Cooke, 2006).

Functional imaging studies in humans show that targets appearing near a hand selectively activate and cause adaptation in the intraparietal sulcus (IPS; Makin et al., 2007), supramarginal gyrus (SMG), and in both the dorsal and ventral premotor cortex (PMd and PMv, respectively) in comparison to targets appearing far from the hand (Brozzoli et al., 2011). Other work (Gentile et al., 2011) demonstrated that PMv, PMd, and SMG all showed BOLD-signal increases to near-hand unimodal visual and unimodal tactile stimuli, additive responses to bimodal visual-tactile stimuli, and PMd and anterior IPS showed superadditive responses to bimodal stimuli (i.e., the response to bimodal stimuli was greater than predicted from the sum of responses to unimodal stimuli). Together, these studies suggest that near-hand visual targets recruit multisensory neural resources, like bimodal and multimodal cells, and that these effects are similar both in monkeys and humans. This recruitment may allow for a more robust visual representation of the target, and support the processing benefits associated with near-hand space. This explanation can be likened to the facilitation that appears to explain redundancy effects (the finding that humans respond more quickly to two identical stimuli than to one, even when factors like stimulus size and brightness are controlled; Raab, 1962; Gielen et al., 1983). It may be that visual stimuli appearing near a hand recruit additional (multisensory) brain regions for processing that are not recruited in the hand-absent case, and that this additional recruitment influences visual processing. Tests of a computational model using this general principle have been promising (Magosso et al., 2010b).

Given that motor and sensory representations of the hand are lateralized to the contralateral hemisphere both for simple (Bryden, 1982; Graziano, 1999; Jones and Lederman, 2006) and patterned (Reed et al., 2009) stimuli, our study focuses on whether effects near the left and right hands interact in a meaningful way with a task known to differentially tap the left and right hemispheres (RHs). The general nature of hemispheric specialization is relatively well-known. Classically, language is thought to be lateralized to the left hemisphere (LH) while visuospatial judgments are lateralized to the RH (Kimura and Durnford, 1974; Kinsbourne and Hicks, 1978; Bryden, 1982; Bradshaw and Nettleton, 1983; Corballis, 1989). With regard to specific tasks that demonstrate lateralized visual processing, Navon's (1977) hierarchical forms have been used to study differences between global and local processing and their relative lateralization (e.g., see **Table 1**). In her classic study, Sergent (1982) used hierarchical forms consisting of two target letters, H and L, and two distracter letters, F and S, and asked that participants indicate with a button press whether one of the target letters was present in a stimulus. The target could be present at the global level (the large letter), the local level (the small letter), at both levels, or at neither. Hemispheric specialization was tested by presenting the stimuli either in the left or right visual field, as visual information presented in the left visual field projects to the RH and visual information presented in the right visual field projects to the LH. Sergent found that response latency depended both on target level and visual field. Global-level targets were processed more quickly when the hierarchical figure appeared in the left visual field RH than in the right visual field LH. Conversely, local-level targets were processed more quickly when the hierarchical figure was presented centrally or in the right visual field LH in comparison to the left visual field RH. Sergent (1982) interpreted this pattern as evidence that global information is preferentially processed in the RH and that local information is preferentially processed in the LH.

Table 1 | Experimental stimuli, hierarchical form displays of global target-present (large letters X and O) and global target-absent items (large letters T and U) composed of local target-present (small component Xs and Os) and local target-absent items (small component Ts and U).

	Global level	
Local level	Target present	Target absent
Target present		
Target absent		

*Example stimuli shown during instructions.

Sergent (1982) and other researchers have acknowledged that the distinction between global and local processing may come down to a distinction between visual processing of low and high spatial frequency information, respectively (Shulman et al., 1986; Christman et al., 1991; Kitterle et al., 1992; Flevaris et al., 2010, 2011). In general, these studies associate global/low-spatial-frequency processing with RH function and local/high-spatial-frequency with LH function (Karim and Kojima, 2010). This lateralization pattern has been supported by studies of neuropsychological patients (e.g., Delis et al., 1986) and in studies using electroencephalography (e.g., Martens and Hubner, 2013) and functional imaging techniques (e.g., Fink et al., 1997).

Do people process visual information appearing near their left or right hands differently? In their study of cortically-blind participant MB, Brown et al. (2008) presented stimuli in the blind (upper-left) field and found that he was able to reliably indicate target size when he placed his left hand near the display (a configuration in which both visual field and hand are linked to the same RH), but not when he placed his right hand near the display. More recently, Tseng and Bridgeman (2011) found that participants performed a change-detection task more accurately when they placed both hands near the display in comparison to a no-hands condition, and also found that the right hand was somewhat more effective than the left hand in facilitating change detection. Tseng and Bridgeman concluded that facilitation in this change detection task was driven by a hand-related facilitation of visual working memory that reflects the frequency with which we commonly interact with objects. Le Bigot and Grosjean (2012) asked healthy right- and left-handed participants to perform an unspeeded visual discrimination task with the left hand, right hand, or both hands on the display, or no hands near the display. Both right- and left-handers demonstrated greater visual sensitivity near their dominant hand in comparison to their non-dominant hand. While right-handers did not show any benefit near their non-dominant left hand, left-handers did show some facilitation near their non-dominant right hand. Finally, Lloyd et al. (2010) showed greater effects of hand proximity in their target-discrimination task when the target appeared near the right hand. Importantly, Lloyd et al. avoided using the hands both as a manipulation and as an effector and instead asked participants to respond with their feet. Interestingly, they found that the right-hand proximity effect was significant only when participants responded with their right foot. Together, this set of studies indicates that the left and right hands may have differential effects on visual processing of nearby targets, but because these experiments did not explicitly test for interactions with cerebral lateralization, the following question remains unanswered.

Do the left and right hands have differential effects on the processing of nearby visual stimuli? The goal of this study was to test the hypothesis that presenting visual stimuli near the left hand preferentially recruits visual processing mechanisms lateralized in the RH, and also whether presenting visual stimuli near the right hand preferentially recruits visual processing mechanisms lateralized in the LH. To test this hypothesis, we capitalized on previous research showing that global and local visual information are processed preferentially in the right and LH, respectively (Sergent, 1982). Hierarchical letters were presented centrally and participants placed either their left or right hand nearby, or kept both hands far from the display. In an "attend-global" task, participants reported whether the target was present or absent at the global level as quickly as possible, and in an "attend-local" task, participants reported whether the target was present or absent at the local level as quickly as possible with their feet. We predicted that if visual stimuli appearing near the left hand preferentially recruit resources in the RH, then global-level processing should be facilitated in the left-hand present condition as compared to the right-hand present and hand-absent conditions. By contrast, if visual stimuli appearing near the right hand preferentially recruit resources in the LH, then local-level processing should be facilitated in the right-hand present condition as compared to the left-hand present and hand-absent conditions.

METHODS

PARTICIPANTS

Thirty-one undergraduate students (mean age = 22.0 ± 6.64, range = 17–42) at Trent University participated in this study for extra credit or renumeration. All reported being strongly right-handed, with handedness scores greater than 28 on the Dutch Handedness Questionnaire (Van Strien, 1992). All had normal or corrected-to-normal visual acuity and no neurological history. The Trent University Research Ethics Board approved all procedures and each participant gave written informed consent before participation.

APPARATUS

Participants sat at a table and kept their head fixed in a chin rest with their feet resting on an electric piano (Yamaha PSR-270, Buena Park, CA) beneath the table (See **Figure 1A**). Displays were projected downward onto the table surface using an LCD projector (refresh rate = 75 Hz; Optoma DLP EP739, Mississauga, ON) onto a display space that was defined by a 66.0 × 50.8 cm sheet of matte black paper used to limit reflection. Displays were hierarchical forms (**Table 1**) created using GIMP (GNU Image Manipulation Program, The GIMP Development Team) and presented centrally in the display space in white against the black background of the experiment.

The experiment was programmed using the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) for Matlab (The Mathworks™, Natick, MA). Response time (RT) data were collected on the same desktop computer receiving output from the electric piano placed at participants' feet. Participants made target-present/absent responses by pressing the piano keys with one foot or the other according to their assigned foot-response mapping. An algorithm in Matlab was used to detect the onset of the sound signal to determine RT. Matlab sampled the sound card directly at a rate of 16,384 Hz, and a Fourier transformation was used to determine whether the fundamental frequency of the signal was below or above a cutoff criterion. Low pitched tones represented a left-foot press and high-pitched tones represented a right-foot press. Pilot tests revealed 100% left-right classification accuracy.

DISPLAYS

Displays consisted of hierarchical forms using small characters as local elements to compose large characters as the global elements (see **Table 1**). Target items were Xs or Os and non-target items were Ts and Us. These characters were chosen for their symmetry and similar proportion of straight (X and T) and curved (O and U) features, and all were presented in a sans serif font. Each display was 5 × 5 cm and spanned 6.0 degrees of visual angle (internal letters 0.9°) when presented at the mean viewing distance of 48 cm. Any given stimulus had a target located at both global and local levels, just the global level, just the local level, or no targets present at either level. All possible target configurations are presented in **Table 1**.

DESIGN

The experiment utilized a 2-task (attend global, attend local) × 3-hand (absent, left, right) × 2-target level (global vs. local) × 2-target presence (present, absent) within-subjects design. Each participant completed 2 versions of the target-detection task, which were blocked and counterbalanced across participants. In the attend-global task, participants were instructed to make their target-presence judgments on the large letter in the display and ignore the small component letters. In the attend-local task, participants were instructed to make their target-presence judgments on the identity of the small letters in the display while ignoring the large global letter. Hand was also blocked. Within each task level, participants completed 3 hand-level blocks: left-hand present, right-hand present, and hand-absent. Hand-level order was counterbalanced across participants. Target level was presented pseudorandomly throughout the experiment such that there were an equal number of stimuli with targets present and absent at the global and local levels in each task-condition (see **Table 1** for target levels in experimental stimuli). At the beginning of each task, participants completed a 16-trial (hand-absent) practice block. Each of the 16 stimuli (**Table 1**) was presented three times per experimental block. Thus, the experiment consisted of six 48-trial blocks. Participants were provided with feedback about their speed (mean reaction time in ms) and accuracy (percent correct) after every 24 trials. Foot-response mapping was counterbalanced between participants such that half of the participants used the left foot for target-present responses and their right-foot for target-absent response, and the other half used the reverse mapping.

PROCEDURE

Participants were instructed on how to perform the first task condition with the aid of example stimuli that were chosen to demonstrate target presence and absence at the local and global levels (see **Table 1**). Participants were instructed about their assigned foot-response mapping and instructed to respond as quickly as they could while aiming for an accuracy rate of at least 90%. Participants completed a practice session for their assigned first task, and then completed the three experimental blocks for the assigned first task, one block for each of the three hand conditions. This process was then repeated for the second task condition.

For the left- and right-hand conditions, participant were asked to make a pointing posture with the hand of interest and place their index finger on a position marker presented 2 cm below the stimulus at the start of each experimental block. Participants kept their hand in this position and posture for the duration of experimental trials (see **Figure 1B**) while keeping their other hand away from the display by resting it on their lap. In the hand-absent condition participants were asked to keep both hands resting on their lap.

Each trial began with the presentation of a fixation cross in the centre of the display for a random duration between 1000 and 2000 ms. The display was then presented for 200 ms followed by a blank screen. Participants had a further 2750 ms to make their response (see **Figure 1B**). The experiment lasted for approximately 45 min.

RESULTS

Reaction time (RT) (ms) was recorded as participants made target-present/absent judgments about displays. The percentage of correct responses was calculated to measure each participant's performance accuracy. Before performing our statistical analyses, the following steps were taken. Participants whose overall accuracy rating failed to reach 90% were eliminated from the analysis. This resulted in the removal of two participants, leaving 29 participants' data for analysis. Trials in which participants did not respond were excluded from the analysis, resulting in the removal of 0.08% of the data. RT outliers were identified using the following rules. RTs lower than 100 ms were removed as research shows that participants need at least 90 ms to respond to newly-presented visual information (Paulignan et al., 1991). The overall mean and standard deviation of reaction time (ms) were determined from the remaining data and RTs greater than the mean plus four standard deviations (1500 ms) were removed, resulting in the loss of 0.10% of the data. Overall mean accuracy was 96.2 ± 2%. The arcsine transformation of proportion correct values within each cell of the design for each participant was calculated and these values used to analyse accuracy (Cohen and Cohen, 1983; Dixon, 2008). Incorrect responses were removed before mean reaction time for each cell of the design for each participant was calculated. These means were used to analyse reaction time.

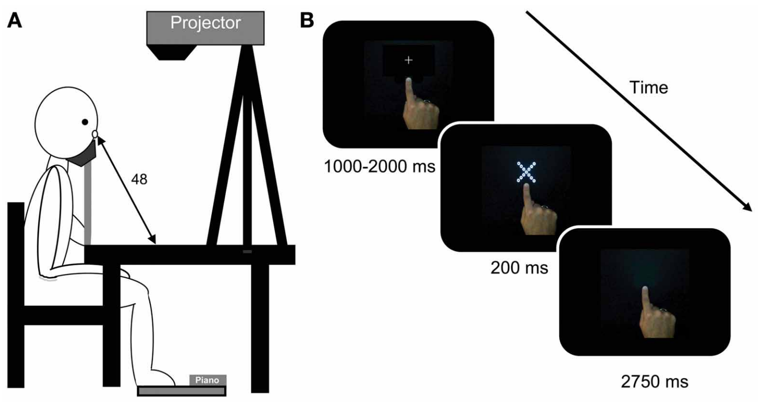


FIGURE 1 | (A) The picture on the left depicts a participant sitting at the table where the display was projected by a projector mounted on a tripod. The participant responded by depressing the keyboard with his/her feet. **(B)** shows trial events in a typical right-hand near condition trial. The first screen was presented with the central fixation cross. The fixation was replaced by a hierarchical stimulus for 200 ms. This stimulus was removed and participants had up to 2750 ms to make their response. The trial ended and the next fixation was shown as soon as the response was made. Note: stimuli do not photograph as sharply as they appeared to participants.

GLOBAL PROCESSING IS FACILITATED BY LEFT- BUT NOT RIGHT-HAND PRESENCE

Figure 2A shows mean reaction time as a function of hand condition and global target presence in the attend-global task only. We hypothesized that because global processing is linked to the RH, and because sensory processing for the left hand is also linked to the RH, placing the left hand near the display would recruit RH resources that would facilitate global processing. This hypothesis predicted that global target discrimination would be faster when stimuli were presented near the left hand than in the right-hand or no-hand conditions. We coded target presence according to whether the target was present or absent at the global level and then submitted RT data for correct responses to a 3-hand (left, right, absent) × 2-target presence (global-target present, global-target absent) repeated-measures analysis of variance (ANOVA, $\alpha = 0.05$). We found significant main effects of target presence, $F_{(1,\,28)} = 55.75$, $p < 0.001$, hand, $F_{(2,\,56)} = 3.59$, $p = 0.033$, and no significant interaction, $F_{(2,\,56)} = 0.21$, $p = 0.881$. Regarding the main effect for target presence, participants responded 48 ± 2 ms more quickly to global target-present stimuli than to target-absent stimuli. To determine the nature of the hand-presence effect we conducted planned comparisons (least significant difference (LSD), df = 28, $\alpha = 0.05$) of mean RT for the three hand conditions. Responses were 20 ± 4 and 18 ± 4 ms faster with the left hand in the display in comparison to the right-hand and no-hand conditions, respectively (ps < 0.001). The right hand did not differ from the hand-absent condition (1.6 ± 4 ms), $p = 0.917$. Participants performed the global target-detection task more quickly when their left hand was in the display than when no hand or their right hand was present.

Although we eliminated participants who failed to achieve 90% correct overall, there remained a small possibility that the effect of hand on reaction time came at the expense of a shifted criterion for accuracy. To check for this possibility, we submitted the arcsine transformation of mean percent correct to the same ANOVA. This analysis revealed no significant effect of hand ($p = 0.560$), global target presence ($p = 0.438$), and no interaction ($p = 0.242$). Overall, participants completed the task with 96.4 ± 0.3% accuracy and the evidence suggests that they did not trade accuracy for speed when performing this task.

LOCAL PROCESSING IS NOT SENSITIVE TO HAND-PRESENCE

Figure 2B shows mean reaction time as a function of hand condition and local target presence in the attend-local task only. We hypothesized that because local processing is carried out predominantly in the LH, placing the right hand near the display would recruit LH resources that would facilitate local processing. This hypothesis predicted that local target discrimination would be faster when stimuli were presented near the right hand than in the left-hand or no-hand conditions. We coded target presence according to whether the target was present or absent at the local level and then submitted mean RT data for correct responses to a 3-hand (left, right, absent) × 2-target presence (local-target present, local-target absent) repeated-measures ANOVA. This analysis revealed a significant main effect of local target presence, $F_{(1,\,28)} = 34.78$, $p < 0.001$. Mean reaction times for local target-present items were 46 ± 3 ms faster than for target-absent items. There was no significant main effect of hand, $F_{(2,\,56)} = 0.070$, $p = 0.932$, nor was there a significant interaction between hand and local target presence, $F_{(2,\,56)} = 2.57$, $p = 0.086$. Contrary to our predictions, placing the right hand near the display did not influence local processing[1].

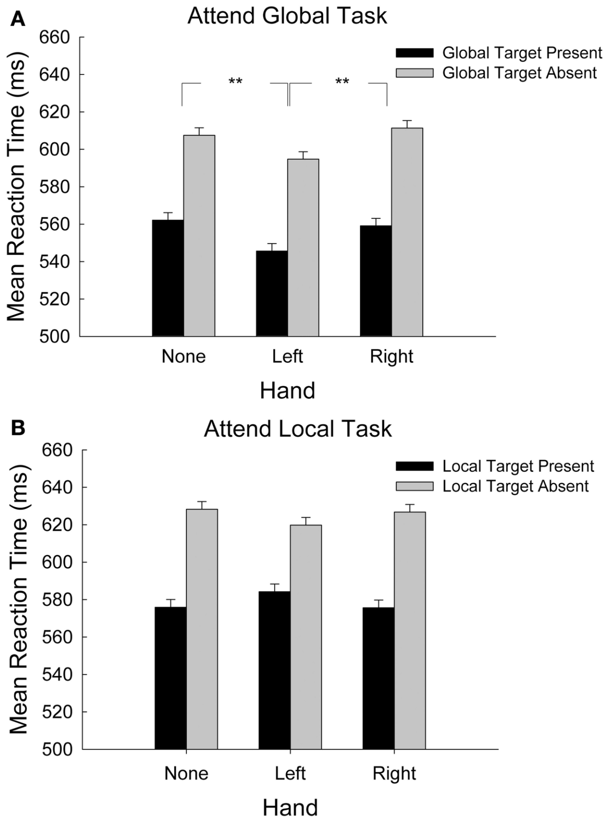


FIGURE 2 | (A) Mean response time during the attend-global task, where global targets were present or absent, plotted by hand-presence condition. Error bars represent standard error of the mean. **(B)** Mean response time during the attend-local task, where local targets were present or absent, plotted by hand-presence condition. Error bars represent standard error of the mean $^{**}p < 0.001$.

Our analysis of accuracy revealed no significant effect of hand ($p = 0.685$), global target presence ($p = 0.137$), and no interaction ($p = 0.808$). Overall, participants completed the task with 96.0 ± 0.3% accuracy and the evidence suggests that they did not trade accuracy for speed when performing this task.

GLOBAL PROCESSING COMPARED TO LOCAL PROCESSING.

To investigate effects of task and to determine if response foot influenced the speed with which participants responded to the displays, we submitted mean RT for correct responses only to

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[1] Although there is a pattern in the attend-local means suggesting that the left hand may interfere with "yes" responses to local target-present displays and facilitate "no" responses to local target-absent displays, an analysis of simple main effects of hand within each target level revealed no significant differences between hand presence in either the target present [$F_{(2,\,56)} = 0.59$, $p = 0.557$] or target-absent [$F_{(2,\,56)} = 0.76$, $p = 0.474$] conditions.

a 2-foot (left, right) × 2-task (attend-global, attend-local) × 3-hand (left, right, absent) × 4-target level (double target, single global target, single local target, no target) mixed ANOVA. This analysis revealed a main effect of task $F_{(1,\ 28)} = 11.80$, $p = 0.002$; participants performed the the attend-global task (576 ± 16 ms) significantly faster than the attend-local task (603 ± 12 ms). The ANOVA also revealed a task by target interaction, $F_{(3,\ 84)} = 29.18$, $p < 0.001$. Simple main effects analyses showed that when participants attended globally, there was no significant difference between responses to target-absent displays (602 ± 16 ms) and single local target displays (601 ± 16 ms; $p = 0.892$), indicating that when participants attended to the global level, they were not distracted by the presence of a target at the local level ($p = 0.892$). By contrast, when participants attended locally, they discarded target-absent displays (615 ± 12) significantly more quickly than they discarded displays with a target at the global level, $F_{(3,\ 84)} = 55.07$, $p < 0.001$. These results are reflective of the global precedence effect (Navon, 1977).

Consistent with the analyses reported earlier, this ANOVA revealed a marginal interaction of task and hand, $F_{(2,\ 56)} = 2.73$, $p = 0.073$. Planned analyses based on our predictions revealed that in the attend-global task, there was a significant effect of hand, $F_{(2,\ 56)} = 3.89$, $p = 0.026$. Comparisons between means (LSD, $df = 28$, $\alpha = 0.05$) indicate that participants responded significantly more quickly when their left hand was placed near the display (563 ± 16) than in the right hand (583 ± 15 ms; $p = 0.032$) or no hand (581 ± 16 ms; $p = 0.003$) conditions. There was no difference between the left and right hands ($p = 0.901$). By contrast, in the attend-local task, no difference between hand conditions was revealed, $F_{(2,\ 56)} = 0.01$, $p = 0.991$. There were no other main effects or interactions involving hand.

Finally, this analysis revealed no significant main effect of foot, $F_{(1,\ 28)} = 1.78$, $p = 0.19$, and no significant interactions between foot and hand, $F_{(2,\ 56)} = 0.12$, $p = 0.890$, task, foot, and hand, $F_{(2,\ 56)} = 0.08$, $p = 0.923$, foot, target, and hand, $F_{(3,\ 84)} = 1.75$, $p = 0.113$, or foot, hand, task, and target, $F_{(6,\ 168)} = 1.28$, $p = 0.268$, indicating that response side (foot) did not influence the effect of the hand. There was a significant main effect of target, $F_{(3,\ 84)} = 81.32$, $p < 0.001$, and a significant interaction between foot and target, $F_{(3,\ 84)} = 8.59$, $p < 0.001$. Participants responded to double stimuli (550 ± 15 ms) significantly more quickly than to all other stimuli [global level alone (600 ± 14 ms); local level alone (599 ± 14 ms); no-target stimuli (608 ± 14 ms; all *p*s < 0.04)]. The interaction with foot was driven by the finding that differences between double-level targets and other targets were greater for the right (107 ± 16 ms) than left foot (36 ± 18 ms).

When the same 4-way ANOVA was applied to measures of response accuracy, a significant interaction of hand and foot was revealed, $F_{(2,\ 56)} = 4.16$, $p = 0.021$. Curiously, when there was no hand in the display, there was no difference in the accuracy of responses made by the right (96.5 ± 0.7%) and left (95.7 ± 0.7%) feet. Simple main effects analyses revealed, however, that when either hand was present in the display, left foot accuracy (97.3 ± 1.0%) was significantly better than right foot accuracy (94.3 ± 1.0%). This effect did not interact with task, $F_{(2,\ 56)} = 0.397$, $p = 0.674$, or with target type, $F_{(3,\ 84)} = 0.118$, $p = 0.889$. Importantly, there was no task by hand interaction, $F_{(2,\ 56)} = 0.230$, $p = 0.795$ indicating that participants did not trade speed for accuracy in this task.

ARE GLOBAL ITEMS PROCESSED BEFORE LOCAL ITEMS?

To determine whether our stimuli assessed global and local processing in the manner we claim and in a manner consistent with past research, we checked our manipulation with the following analysis. According to Navon (1977) and Gestalt psychologists before him, global processing takes less time than local processing because humans are obligated to determine the global percept first. Alternative accounts of global precedence highlight the possibility that it may simply be easier to direct attention to the global, low-frequency stimulus level than the local, high-frequency stimulus level (e.g., Miller, 1981; Kimchi, 1982). Regardless, to assess whether this expected outcome was present in this study, we compared responses to displays with double targets (target present at both global and local levels) to those with a single target (target present at the attended level only) within each task. We also assessed the role that the nearby hand might play in the global precedence effect. We submitted mean RT to a 2-task (attend-global, attend-local) × 3-hand (left, right, absent) by 2-target type [double targets (target present at both the global and local level), single targets (targets present at the attended level only)] repeated measures ANOVA. The results are presented in **Figure 3**. The analysis revealed a significant interaction of task and target type, $F_{(1,\ 28)} = 7.73$, $p = 0.009$, and significant main effects for both task, $F_{(1,\ 28)} = 13.38$, $p = 0.001$, and target type, $F_{(1,\ 28)} = 131.69$, $p < 0.001$. For the attend-global task, participants responded to single target stimuli 37 ± 2 ms more slowly than double-target stimuli, and in the attend-local task, participants responded to single-target stimuli 61 ± 3 ms more slowly than to double-target stimuli. A simple main effects analysis revealed that the interference induced by non-targets at the unattended level (in single target stimuli) was significantly greater in the attend-local task than the attend-global task, $F_{(1,\ 28)} = 7.81$, $p = 0.009$.

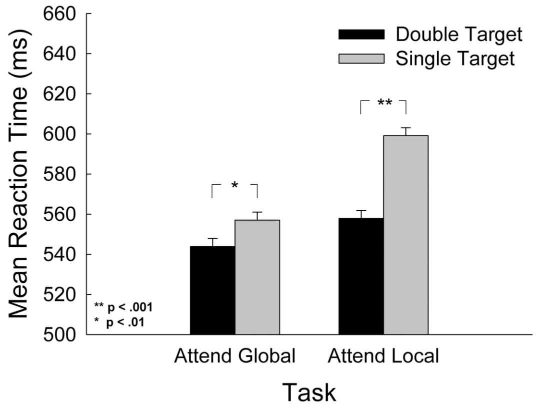

FIGURE 3 | Mean response time as a function of task and of target level, where double target contained a target at both the global and local levels, and single targets contained a target at the attended level only. Error bars represent standard error of the mean.

This analysis also revealed a marginal interaction of task and hand, $F_{(2, 56)} = 2.55$, $p = 0.087$. Planned comparisons revealed that in the attend-global task, there was a significant main effect of hand, $F_{(2, 56)} = 4.92$, $p = 0.011$. Comparisons between means (LSD, df = 28) revealed that participants responded 19 ± 3 ms more quickly when the left hand was in the display in comparison to no hand ($p < 0.001$) and 19 ± 4 ms more quickly in comparison to the right hand ($p = 0.005$). There were no significant differences between hand conditions in the attend-local task, $F_{(2, 56)} = 0.222$, $p = 0.802$. There was no interaction between hand and target type. In sum, there is a greater cost for detecting single targets at the local level than at the global level. This finding is consistent with the long-standing global precedence effect and is an indicator that our stimuli adequately tapped global/low-frequency and local/high-frequency processing.

DISCUSSION

The purpose of the present study was to investigate the possibility that hand laterality and hemispheric lateralization of visual function interact to produce differential visual processing advantages near the left and right hands. We presented hierarchical forms near participants' left or right hands as well as in a hand-absent condition to investigate possible interactions with global and local processing, which have been linked to processing in the right and LHs, respectively. We predicted that global visual processing would be facilitated by placing the left hand near the stimulus, and that local processing would be facilitated by placing the right hand near the stimulus. We found that left-hand presence significantly improved the speed of discrimination of global-level targets in comparison to right-hand and hand-absent conditions. This improvement in global processing near the left hand was not achieved by compromising accuracy. This result is consistent with the possibility that the presentation of the target near the left hand preferentially recruited processing resources associated with the RH. We did not find that right-hand presence influenced local processing. Explanations for this pattern are presented below.

GLOBAL PROCESSING FACILITATED BY PRESENTING HIERARCHICAL STIMULI NEAR THE LEFT HAND

Participants discriminated global-level targets more quickly when their left hand was present near the display in comparison to right-hand present or hand-absent conditions. One possible explanation for this finding is that the presentation of the stimulus near the hands recruited visual-tactile bimodal cells linked to the hand in the contralateral RH (Graziano et al., 1994; Graziano, 1999) and that this recruitment preferentially facilitated right-hemisphere-dominant visual processing. Electrophysiological studies in monkeys have shown that these neurons, recorded in the hemisphere contralateral to the hand, have tRFs on the skin and vRFs that include and extend beyond the tRF into the space surrounding the hand. They are activated in response to either a tactile or a visual stimulus presented on or near the skin (Graziano and Gross, 1993; Graziano et al., 1994; Graziano, 1999; Graziano and Gandhi, 2000; Graziano and Cooke, 2006). It may be that presenting the hierarchical stimulus near the hand recruited bimodal neurons in the contralateral hemisphere and that they contributed to the visual processing of the stimulus. When the left-hand was placed near the stimulus, this recruitment facilitated global processing for two reasons. First, and most importantly, global processing was facilitated because both global processing and the sensory representation of the left hand are linked strongly to the RH. Second, global processing precedes local processing (Navon, 1977), unfolding relatively early in the stream of visual processing. Evidence suggests that near-hand effects influence relatively early aspects of perception, like figure-ground segregation (Cosman and Vecera, 2010). More recently, research has demonstrated that hand presence may preferentially activate the temporally-sensitive magnocellular visual pathway while inhibiting the spatially-sensitive parvocellular visual pathway (Gozli et al., 2012). Therefore, one possibility is that the observation of left-hand facilitation of global processing depends both on (1) the congruency between left-hand sensory processing and global processing dominance in the RH, and (2) the notion that both hand-presence and the grouping mechanisms that give rise to the global percept act relatively early in the stream of visual processing (Pomerantz and Pristach, 1989; Moore and Egeth, 1997; Gozli et al., 2012).

LOCAL PROCESSING OF HIERARCHICAL STIMULI DID NOT BENEFIT FROM NEAR-HAND PRESENCE

Hand presence near the display did not influence either the speed or accuracy with which participants discriminated targets at the local level. It is possible that the current task failed to demonstrate clear near-hand effects for local processing because hand effects happen relatively early in the stream of visual processing (Cosman and Vecera, 2010) whereas local processing happens later (Navon, 1977). Our analysis of the global precedence effect indicates that people have more difficulty discarding a global distractor than a local distractor. Our hand condition did not interact with these effects, which is somewhat inconsistent with the findings of Davoli et al. (2012) who found that switching attention between global and local levels was delayed by the presence of two hands near the display. There are several key differences between their study and this one, however, that may explain this inconsistency. First, we did not have a two-hand condition in our experiment, and second, Davoli et al. (2012) asked their participants to not only switch from a global identification task to a local identification task within one trial, but they also asked their participants to switch from one stimulus to another. These differences make the two experiments very difficult to compare. In general, we believe that these attend-local findings are consistent with the proposal that global processing happens early and is obligatory (Navon, 1977; Conci et al., 2011), whereas local processing happens later and may not be obligatory. Since local information is dealt with later, it may be more difficult to isolate hand effects on local processing using response time measures.

POSSIBLE EXPLANATIONS FOR NEAR-HAND EFFECTS

Explanations for near-hand effects have been offered both at cognitive and neural levels and it is important to understand these effects at both levels. In general, cognitive-level accounts (Reed et al., 2006, 2010; Abrams et al., 2008; Cosman and Vecera, 2010; Tseng and Bridgeman, 2011; Davoli et al., 2012), have focused on explaining the conditions that invoke facilitation vs.

interference and often examine the effects of placing both hands near the display. In general, cognitive-level explanations have been compatible with neural-level explanations.

One possible explanation is that improved visual processing of targets appearing near a passively resting hand is simply an epiphenomenon of the roles that sensory and motor systems play in covert preparation for action (Reed et al., 2010; Gozli et al., 2012; Makin et al., 2012). Objects presented near the hands are often associated with actions and these potential actions demand effective coding of stimulus location with respect to our limbs so that we can interact with our environment efficiently. For example, during a reaching action, grip and/or trajectory adjustments may be needed to improve the movement's completion or respond to unexpected target motion. As such, the activation of bimodal cells by near-hand targets may work to represent the target in a hand-centred frame of reference that is better prepared to initiate new actions or adjust ongoing ones, if need be (Reed et al., 2010; Makin et al., 2012). Bimodal cells may also play a role in acting quickly on visual targets that appear suddenly within peripersonal space (Graziano and Cooke, 2006).

While this possibility requires further testing, it does not appear to explain the data we present here. Evidence suggests that visual processing for reaching and grasping is lateralized to the LH, even in left-handers (Gonzalez et al., 2006). This lateralization predicts that, regardless of the task participants were performing, if participants were covertly preparing to grasp our hierarchical stimuli, we should have observed an effect of placing the *right* hand near the stimuli. The effect we present here is clearly linked to the near left hand.

We believe that the differential effect of the nearby left and right hand on global processing described here can be explained by a bimodal-recruitment model that takes into account the lateralized sensory processing associated with each hand. When a target appears near a hand, bimodal cells are recruited to help process the target, whereas when the hand is not nearby the target, these cells are not recruited. We propose that the additional activation of bimodal cells in the near-hand case improves the representation of the target. The near-hand visual representation of the target is more robust, more resolute, and therefore, responses can be made earlier and with less variability. This explanation is like the one used to explain redundancy gains (e.g., Raab, 1962; Gielen et al., 1983). Redundancy gains are explained by the notion that two identical stimuli recruit more resources than one stimulus, and that these resources either combine or compete for response activation, leading to better performance in the two-stimulus condition (e.g., Mordkoff and Yantis, 1991; Mordkoff and Miller, 1993). Support for this explanation of near-hand effects can be derived from previous studies showing reductions in the variability of size-estimation and grasping (Brown et al., 2008), targeted-reaching performance (Brown et al., 2009), and improvements in signal sensitivity (Dufour and Touzalin, 2008; Le Bigot and Grosjean, 2012) in near-hand conditions. Together, these findings suggest that reductions in variability reflect reductions in noise as additional (bimodal) neurons are recruited for processing. Thus, presenting targets near the hand may result in an overall improvement in the signal-to-noise ratio (SNR).

An additional part of this explanation relies on the possibility that bimodal-cell recruitment is lateralized to the hemisphere contralateral to the hand of interest. Because tactile responses are highly lateralized to the hemisphere contralateral to the hand (Bryden, 1982; Graziano, 1999; Jones and Lederman, 2006; Reed et al., 2009), we surmise that bimodal cell responses are lateralized in a similar manner. Functional imaging studies are consistent with this idea. All reports of brain activation to visual targets appearing near a hand primarily show activation in the hemisphere contralateral to the hand (Makin et al., 2007; Brozzoli et al., 2011; Gentile et al., 2011). If the activation of bimodal cells in response to visual stimuli appearing near the hand is largely confined to the contralateral hemisphere, then we propose that this activation will have preferential access to any specialized visual processing happening there. Our finding that global processing, a preferentially right-hemisphere function, benefits from having the left but not the right hand near the target is consistent with this notion.

While this possibility also requires further testing, a computation model developed on the basis of similar assumptions has had success reproducing near-hand (Magosso et al., 2010a) and near-tool effects (Magosso et al., 2010b) in humans. The model assumes that the left and RHs initially code space near the left and right hands independently, and that interactions between hemispheres happen after a near-hand stimulus has been coded by a visual system, a tactile system, and then by a downstream visual-tactile system that integrates visual and tactile information from space near and on the hands. Tests of the model have revealed that this relatively simple architecture can reproduce effects demonstrated in studies of humans, including the reinforcement of unisensory perception by multimodal activation.

CONCLUSION

In short, the nature of near-hand effects may rely both on which hand appears near the display and hemispheric specialization: stimuli appearing near a hand may recruit bimodal visual-tactile neurons in the contralateral hemisphere, stimulating lateralized visual processing mechanisms there. The data we present here provide partial support for this hypothesis.

AUTHOR CONTRIBUTIONS

Liana E. Brown, Robin M. Langerak, and Carina La Mantia conception and design of research; Robin M. Langerak performed experiments; Robin M. Langerak and Liana E. Brown analyzed data; Robin M. Langerak and Liana E. Brown interpreted results of experiments; Robin M. Langerak and Liana E. Brown prepared figures; Robin M. Langerak, Carina La Mantia and Liana E. Brown drafted manuscript.

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Hand proximity facilitates spatial discrimination of auditory tones

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The effect of hand proximity on vision and visual attention has been well documented. In this study we tested whether such effect(s) would also be present in the auditory modality. With hands placed either near or away from the audio sources, participants performed an auditory-spatial discrimination (Experiment 1: left or right side), pitch discrimination (Experiment 2: high, med, or low tone), and spatial-plus-pitch (Experiment 3: left or right; high, med, or low) discrimination task. In Experiment 1, when hands were away from the audio source, participants consistently responded faster with their right hand regardless of stimulus location. This right hand advantage, however, disappeared in the hands-near condition because of a significant improvement in left hand's reaction time (RT). No effect of hand proximity was found in Experiments 2 or 3, where a choice RT task requiring pitch discrimination was used. Together, these results that the perceptual and attentional effect of hand proximity is not limited to one specific modality, but applicable to the entire "space" near the hands, including stimuli of different modality (at least visual and auditory) within that space. While these findings provide evidence from auditory attention that supports the multimodal account originally raised by Reed et al. (2006), we also discuss the possibility of a dual mechanism hypothesis to reconcile findings from the multimodal and magno/parvocellular account.

Keywords: embodied cognition, hand-altered vision, peripersonal space

INTRODUCTION

The effect of nearby-hands on vision has been well documented since the seminal study by Reed et al. (2006). In a series of studies, Reed et al. found that the placement of a single hand near a potential target location can speed up participants' reaction time (RT) toward that location in the Posner's paradigm (Posner, 1980; Reed et al., 2006). This effect was strongest when one's own hands were visible beside the display, but still remained effective when only visual (i.e., fake hands) or proprioceptive (i.e., covered hands) signals were present (Reed et al., 2006). A series of follow-up experiments by Abrams et al. (2008) found a slower visual search rate when hands were placed near the display, and the authors suggested that the hands perhaps created a stronger but nonselective attentional engagement toward the stimuli around them. This hypothesis would reconcile the seemingly contradictory findings of faster target detection (Reed et al., 2006) and slower visual search (Abrams et al., 2008), because attention is unnecessarily allocated to the distractors in the latter case. Consistent with Abrams et al.'s proposal, subsequent studies also reported slower learning of visual context (Davoli et al., 2012b), slower shift between global and local attention (Davoli et al., 2012a,b,c), and increased accuracy in visual memory tasks (Tseng and Bridgeman, 2011).

To offer a mechanistic explanation for these interesting effects of nearby-hands on visual attention, Reed et al. (2006) suggested the possibility of involvement of multimodal neurons that are located in the frontoparietal network, including the premotor and parietal cortex. These regions have been shown to code objects using a body-centered coordinate system, forming a representation of one's peripersonal space using visual, proprioceptive, tactile, and vestibular information (e.g., Graziano and Botvinick, 2002). The network also selectively responds to both visual and tactile events near the hands (Graziano and Gross, 1995), which accounts for Reed et al.'s (2006) behavioral findings well (for a review, see Tseng et al., 2012; Brockmole et al., 2013). Importantly, studies have now shown that nearby sounds, or auditory information in general, can also elicit responses from these multimodal neurons both in the premotor (Graziano et al., 1999) and parietal cortex (Schlack, 2005), suggesting that auditory information is also integrated into a coherent multimodal or supramodal representation of peripersonal space (Andersen, 1997; Andersen et al., 1997; Serino et al., 2007). One relevant behavioral demonstration comes from Serino et al. (2007), who showed that participants responded to tactile stimulation on the finger faster if a nearby sound was presented (as opposed to a far sound). Although this study is not quite a demonstration of the nearby-hand effect because it is actually the sound that modulates tactile response and not the other way around (e.g., hand presence modulates vision or audition), Serino et al.'s findings nevertheless confirm the possibility of an audio-tactile integration within the peripersonal space.

In light of these findings, the present study investigates whether the effect of hand proximity that has been repeatedly demonstrated in the visuo-tactile domain can also be observed in audition. That is, if the hypothesis of an involvement of the premotor and parietal multimodal neurons offered by Reed et al. (2006) is correct, one should expect to see comparable effects to also take place using auditory stimuli. Thus, in this study we employed a similar two-hands setup used by previous studies (Abrams et al., 2008; Tseng and Bridgeman, 2011), and manipulated hand locations to be either near or far from the audio source (i.e., loudspeakers). Given that previous studies have shown that hand proximity does not generalize to all cognitive tasks, we implemented three different tasks that involved auditory-spatial discrimination, pitch discrimination, and spatial plus pitch discrimination. For example, Davoli et al. (2010) demonstrated that nearby-hands can actually impair the speed of semantic judgment in reading, presumably because the frontoparietal network is more sensitive to spatial information. Therefore, the three experiments included in this study are designed to include both the spatial (location discrimination) and featural (pitch discrimination) components to test whether the same characteristics from vision is also applicable to audition.

EXPERIMENT 1

This experiment used an auditory binary spatial discrimination, a gross form of auditory localization, task, which is analogous to a visual exogenous-orienting task. Participants simply had to respond whether the tone was coming from the left or right, which is a spatial task that relies on purely spatial features of the stimulus. It is reasonable to expect an effect of hand proximity here because similar facilitation in simple RT has been reported in visual orienting paradigms such as a Posner's task (Reed et al., 2006).

METHODS

Participants

Twenty participants (10 male and 10 female; mean age = 22) were recruited from the National Central University. All were right-handed, had normal or corrected-to-normal vision, and were naïve to the purpose of this experiment. All participants gave informed consent prior to the start of the experiment and received monetary payment upon completion of the experiment. The experimental apparatus and procedure was approved by the Institutional Review Board of National Cheng Kung University Hospital, Tainan, Taiwan.

Apparatus and procedure

The experimental setup consisted of a 15-inch computer display, two speakers, and two response pads. The computer display was positioned approximately 45 cm in front of the participants, and displayed only the fixation cross (at the center and near the bottom of the screen where it is closer to the speakers) at the onset of each trial. The loudspeakers, both left and right, were placed underneath and slightly in front of the display (see **Figure 1**), approximately 40 cm in front of the participants.

Participants rested their hands on a platform (not shown in **Figure 1**), where the response pads were mounted. This platform was used for both the hands-near (placed on the table) and hands-far condition (placed on the lap) in order to keep the same gesture and distance intact between both conditions, and also avoid fatigue when the hands were placed on the lap (in the hands-far condition). On this platform, the left and right response pads were approximately 40 cm apart, and both were mounted vertically so that participants' hands mimicked a power grasp position (i.e., left response pad faced left, right response pad faced right, and both palms faced inward with fingers touching the response pads), instead of a flat typing position (see Schultheis and Carlson, 2013; Thomas, 2013, for more on gestures). Throughout the entire experiment, participants placed their hands beside the response pads, with their fingers resting on the response buttons. This gesture was maintained (either on the table or on their lap) throughout the entire block, although participants only had to press the button for a brief period of time for each trial. As such, no arm or elbow movements were required from the participants because the gesture was static, and the participants only had to press the button with their already-in-position fingers.

In the hands-near condition, the left and right speakers were placed within the space between the left and right response pads (**Figure 1**). The left speaker was aligned against the left response pad, and the right speaker against the right response pad. This arrangement in the hands-near condition was designed to induce the percept for participants were leaning their palms and pressing buttons directly against the sides of the speakers. In the hands-far condition, the platform was moved to the participants' lap but

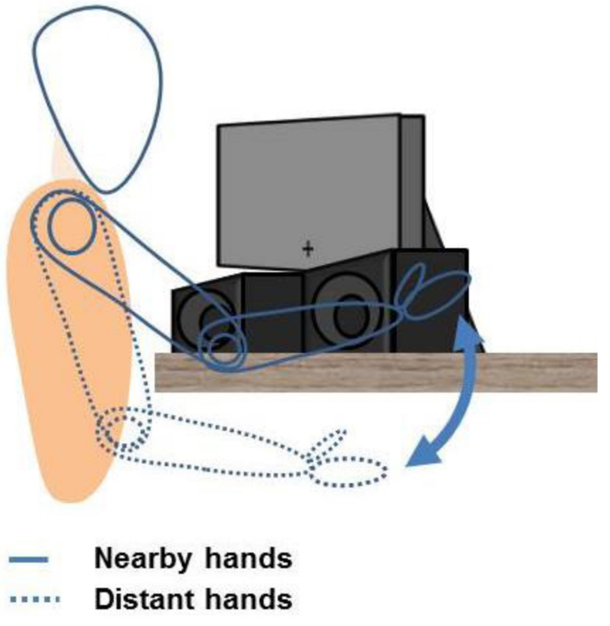

FIGURE 1 | Apparatus and setup of all experiments. Participants placed their hands either on their lap or on the table by the speakers, with the distance between hands (approx. 40 cm) fixed by a platform (not shown). Hands are placed vertically to mimic a power grasp. A fixation cross is displayed at the onset of each trial, allowing both speakers (and hands, in the hands-near condition) to remain visible.

the speakers stayed on the table, and thus everything was kept the same as the hands-near condition except the actual location and visibility of the hands.

On each response pad, there were three buttons (top, middle, bottom), and the participants were instructed to place their index, middle, and ring fingers on the top, middle, and bottom buttons, respectively. Regardless of the different button- and task-requirements between the experiments, this finger-button mapping was used for all the experiments in the present study for the sake of consistency. For all the conditions in this study, participants were instructed to place their chins on a chinrest to avoid any unwanted head movement that would cause unintended perception of uneven volume change coming from the left and right. This also ensured that the ear-to-stimulus distance was kept the same between the hands-near and hands-far conditions.

In Experiment 1, a 600 Hz tone was used. The tone would come from either the left or the right speaker, and participants had to respond with their left or right index fingers by pressing the top button on the left or right response pads, which were placed either by their respective speakers (hands-near condition) or on the participants' left or right lap (hands-far condition). The experiment consisted of two blocks, one hands-near and one hands-far. The order of the blocks was counter-balanced among the participants. In each block, there were 10 practice trials and 60 formal trials. Each trial began with a 1000-ms fixation cross that was positioned toward the bottom of the display, centered above the midline between the two speakers, so that both speakers stayed in view while participants performed the task. This means that although the location of the hands was the key variable of interest here, the visual information associated with the hands inevitably varied between the two conditions (i.e., the hands were not visible to the participants in the hands-far condition). This, however, was done intentionally to maximize the nearby-hand effect because the effect has been suggested to be strongest when one's hands were visible (Reed et al., 2006). The fixation cross was then followed by a 200-ms tone, and participants were told to respond as fast as they could to indicate the side from which the tone came.

RESULTS AND DISCUSSION

Trials with incorrect responses ($<1\%$) were excluded from data analysis. Remaining data were analyzed with a 2×2 repeated-measures ANOVA consisting of factors of hand proximity (near, far) and laterality (left, right). Note that the factor of laterality is simply referring to the tone direction and the responding hand (left or right hand), as the present study used a two-hands setup in the hands-near condition that is similar to Abrams et al. (2008) and Tseng and Bridgeman (2011) instead of the single hand setup by Reed et al. (2006). The effect of hand proximity did not reach statistical significance ($F = 0.106, p = 0.748$), but there was a significant effect of laterality ($F = 8.355, p = 0.009$) and significant interaction between hand proximity and laterality ($F = 8.728$, $p = 0.008$). *Post-hoc* comparisons for the main effect between left and right hand showed a significantly faster RT for the right hand (423.84 ms) over the left hand (437.91 ms). However, *post-hoc* comparisons for the interaction further clarified that the right hand was only faster than the left in the hands-far condition (right: 421 ms, left: 445 ms, $p = 0.002$), whereas the left hand was equally fast as the right hand in the hands-near condition (right: 426 ms, left: 430 ms, $p = 0.46$). Therefore, left-hand RT decreased to be on par with that of the right hand when one's hands were near the audio source (**Figure 2**).

From the results summarized above, we found that auditory localization was facilitated in the left hand when one's hands were both near the auditory source. Specifically, this lack of difference between the left and right hand in the nearby-hand condition was due to the left hand speeding up, relative to the left hand-far condition. The binary auditory localization task used here is somewhat similar to the auditory analogue of a visual detection task, which has been used previously to assess the timing cost of inter-hemispheric transmission (e.g., Jeeves, 1969, 1972; Berlucchi et al., 1971). In the visual detection task, a flash of light is presented either to the left or right visual field. Responses made with the ipsilateral (to the stimulus) hand are slightly but significantly faster than the contralateral hand. The same trend persists even when both hands are crossed, suggesting that the RT difference is best explained by an anatomical account instead of spatial compatibility (Berlucchi et al., 1977). In theory, this is because the perception of the stimulus, as well as the control of the ipsilateral hand, are both mediated by the contralateral hemisphere; whereas the ipsilateral hemisphere would require additional traveling of the signals through the corpus collosum to the other hemisphere for motor output. Unlike these studies, however, in this experiment we did not manipulate the ipsi- and contralateral aspects of the responding hand. That is, in this experiment the left and right hand was always assigned to respond left and right, respectively, thereby maintaining the optimal ipsilateral RT as described by previous studies. Yet, we still observed a right hand advantage over the left hand in RT in the control (hands-far) condition. Indeed, in addition to the ipsilateral hand advantage in RT, when all things are held equal, studies have found that right-handers are consistently faster when responding with their right hand. This is true in detecting visual events (Berlucchi et al.,

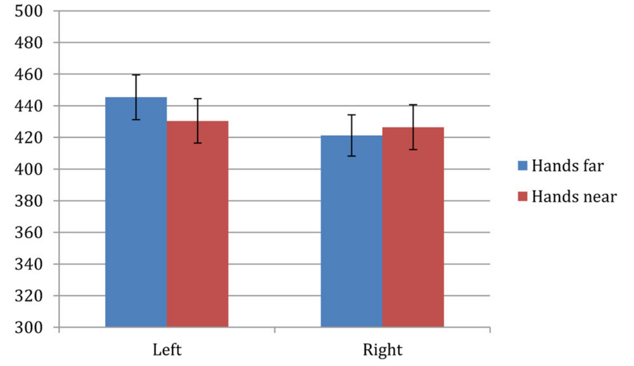

FIGURE 2 | Experiment 1 results. ANOVA revealed a significant interaction between hand proximity and laterality ($F = 8.728$, $p = 0.008$), which was driven by a significant difference between the left and right hand in the hands-far condition (right: 421 ms, left: 445 ms, $p = 0.002$) that became nonsignificant in the hands-near condition (right: 426 ms, left: 430 ms, $p = 0.46$). Therefore, left-hand RT was speeded up to be on par with the right hand when one's own hands were near the audio source.

1971) and using a computer mouse (Peters and Ivanoff, 1999), and has been attributed to the left-hemisphere dominance in right-handers (Berlucchi et al., 1971, 1977). Following this logic, we speculate that hand proximity may have enhanced left-hand RT by bringing participants' right-hemisphere activation above a certain threshold. But, perhaps a more intuitive explanation is that most right-handers have simply hit a ceiling level of response speed with their over-rehearsed right hand. Nevertheless, the left-hand advantage observed here corresponds well with Reed et al.'s (2006) original report of a left hand/side RT advantage, and the current demonstration of the effect of hand proximity in auditory processing supports their multimodal neuron account.

EXPERIMENT 2

In Experiment 1 we observed an effect of hand proximity on binary location discrimination on the left side. However, whether this advantage can be transferred to other forms of auditory tasks, such as featural discrimination, remains to be investigated. One interesting aspect of most nearby-hand studies to date is the spatial nature of many "facilitated" tasks: visual memory (color-location binding), visual search, shifting of visual attention. Therefore, it would be helpful to know if hand proximity would facilitate other processes in the auditory modality when such spatial information is either degraded or made less salient. To this end, in Experiment 2 we used a unidirectional pitch discrimination task to test whether nearby hands would facilitate auditory processing beyond simple discrimination tasks.

METHODS

Participants

A new group of 20 participants (10 male and 10 female; mean age = 21) that did not participate in Experiment 1 were recruited from the National Central University. All were right-handed, had normal or corrected-to-normal vision, and were naïve to the purpose of this experiment. All participants gave informed consent prior to the start of the experiment and received monetary payment upon completion of the experiment. The experimental apparatus and procedure was approved by the Institutional Review Board of National Cheng Kung University Hospital, Tainan, Taiwan. All participants performed well during the practice block and thus no one was excluded from further analysis.

Apparatus and procedure

The apparatus and procedure were mostly identical to those of Experiment 1, with the following exceptions. First, three tones at 400, 600, and 800 Hz were used in the current experiment. For simplicity's sake, we label them as low (400 Hz), med (600 Hz), and high (800 Hz) in this report. Second, the tones emanated from both speakers, thus there was no left or right judgment for this task. Third, participants still placed both of their hands by the speakers, but were instructed to only respond with their dominant (right) hand, using their index, middle, and ring fingers, to indicate high, med, and low tones, respectively. Since the hands were vertically positioned like in Experiment 1 in order to mimic a power grasp (Thomas, 2013), the right fingers were naturally positioned with the index finger at the higher position, the middle finger in the middle, and the ring finger at the lower position. Therefore, participants were told that their high (index), med (middle), and low (ring) positioned fingers are designed to correspond to the high, med, and low tones, respectively, to avoid any confusion over stimulus-response compatibility. Both the hands-near and hands-far blocks began with 21 practice trials, followed by 60 formal trials.

RESULTS AND DISCUSSION

Trials with incorrect responses (<4%) were excluded from data analysis. Remaining data were submitted to a 2 × 2 repeated-measures ANOVA consisting of factors of hand proximity (near, far) and pitch (high, med, low). There was a main effect of pitch ($F = 6.712, p = 0.003$), but no significant effect for hand proximity ($F = 0.009, p = 0.926$) or interaction between hand proximity and pitch ($F = 0.215, p = 0.808$). *Post-hoc* comparisons between high, med, and low tone RTs showed that participants responded faster toward high tones (577 ms) than low ($p = 0.012$) and med ($p = 0.002$) tones, whereas low (633 ms) and med (643 ms) tone RTs were not different from each other ($p = 0.614$). Therefore, there was no effect of hand proximity in this pitch discrimination task.

In this experiment we observed faster RT toward the high tone, presumably because the index finger was faster in pressing buttons than the middle and ring fingers. However, there was no effect of hand proximity in any of the three tones (**Figure 3**). This null result is somewhat surprising, but is consistent with the idea that the effect of hand proximity seem to be less robust when the spatial component in the task is less salient. It is also worth noting that, unlike previous findings, we did not observe a nearby-hand impairment effect here either. This useful difference suggests that the enhanced visual-analysis account that is responsible for the slower shifts of visual attention (Abrams et al., 2008; Tseng et al., 2012; Brockmole et al., 2013) is not applicable to auditory processing; otherwise we should observe a slower RT in the hands-near condition because too much attention is unnecessarily devoted to auditory discrimination. Therefore, auditory processing seems to be less sensitive to the effect of hand proximity.

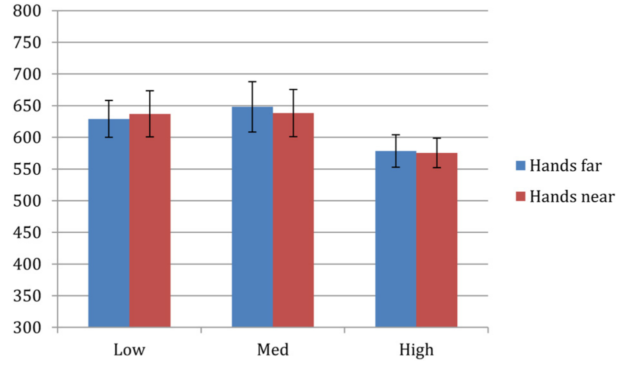

FIGURE 3 | Experiment 2 results. There was a main effect of pitch ($F = 6.712$, $p = 0.003$), but no significant effect for hand proximity ($F = 0.009$, $p = 0.926$) or interaction between hand proximity and pitch ($F = 0.215$, $p = 0.808$).

There are two possible explanations that can account for the findings from Experiments 1 and 2 so far. In Experiment 1, the speeded location discrimination task is essentially a simple RT task, whereas the discrimination task here is a choice RT task due to an additional stage of detailed, featural differentiation. Thus, the first possibility is that nearby-hands are only weakly effective in modulating auditory attention or auditory peripersonal space, and that such an effect is present in simple RT tasks but becomes *insufficient* when more cognitive resources are demanded, such as the case in Experiment 2. The second possibility is that perhaps nearby-hands are sufficient enough to improve RT in both experiments, but did not in Experiment 2 due to *inapplicable* task demands. The rationale for this possibility comes from what we speculate might be a key difference between the current auditory discrimination task and the rest of the literature on visuo-tactile facilitation—the degree of involvement of spatial attention. That is, most visuo-tactile experiments in the current literature are highly spatially-oriented: visual working memory requires featural-spatial binding (Tseng and Bridgeman, 2011) and visual search requires spatial shifts of attention (Abrams et al., 2008). The same applies to visuo-spatial learning (Davoli et al., 2012b) and shifting between global and local scopes of attention (Davoli et al., 2012a,b,c), as well as auditory location discrimination in Experiment 1. Therefore, it is possible that hand proximity does not modulate all aspects of cognitive performance, but only those that would benefit from enhanced spatial attention, be it in vision or audition. In the context of the auditory discrimination task here, then, although spatial attention was indeed enhanced by hand proximity, the unidirectional nature of these acoustic pitches (that are not situated differently in space) could not benefit from an enhanced spatial attention. To test between these two possibilities, a new experiment is needed by adding the localization component to the current discrimination task, so that the discrimination task now becomes spatially relevant.

EXPERIMENT 3

The results from Experiments 1 and 2 raise two possibilities. First, hand proximity may simply be insufficient to modulate anything beyond simple binary localization in the auditory modality. An alternative explanation is that a non-spatial auditory discrimination task is not spatially salient enough to uncover the effect of hand proximity. To test between these two accounts, here we combined the speeded binary localization (Experiment 1) and pitch discrimination (Experiment 2) tasks into one task such that auditory discrimination is now spatially relevant. That is, the high, med, and low tones will either come from the left or right speakers, thus participants must direct their attention spatially and perform the discrimination task. With this design, the "*insufficient*" hypothesis would predict a null result because although even with a spatial task, the task still involves choice RT and is therefore too complex or beyond the involvement of nearby-hand mechanism in auditory peripersonal space. Alternatively, the "*inapplicable*" hypothesis would predict that, with the task being highly spatial (different pitch situated in two different locations), participants would benefit from enhanced spatial attention and show enhanced localization and discrimination.

METHODS

Participants

A new group of 20 participants (10 male and 10 female; mean age = 22) that did not participate in Experiments 1 and 2 were recruited from the National Central University. All were right-handed, had normal or corrected-to-normal vision, and were naïve to the purpose of this experiment. All participants gave informed consent prior at the start of the experiment and received monetary payment upon completion of the experiment. The experimental apparatus and procedure was approved by the Institutional Review Board of National Cheng Kung University Hospital, Tainan, Taiwan.

Apparatus and procedure

The task here was a combination of the localization and discrimination task from Experiments 1 and 2. Participants positioned both hands vertically in a power grasp gesture, and placed them either by the speakers (hands-near) or on their lap (hands-far). The vertical hand placement allowed the same consistent stimulus-response mapping from Experiment 2, where the index finger is positioned on top and is associated with the high tone, the middle finger is positioned in the middle and is associated with the med tone, and the ring finger is positioned at the bottom and is associated with the low tone. The tones were the same as those used in Experiment 2. Critically, the tones would either come from the left or the right speaker like the localization task in Experiment 1, and participants needed to use the correct hand (left, right) and the correct finger (high, med, low) to respond. For example, a med tone from the left should be responded by the left middle finger, and a high tone from the right should be responded by the right index finger. In each block (hands-near, hands-far), participants performed 30 practice trials and 180 formal trials. Everything else was the same as Experiments 1 and 2.

RESULTS AND DISCUSSION

Trials with incorrect responses (<5%) were excluded from data analysis. Remaining data were analyzed with a 2 × 2× 3 repeated-measures ANOVA consisting factors of hand proximity (hands-far, hands-near), laterality (left, right), and pitch (high, med, low). There was a significant main effect of laterality ($F = 10.134$, $p = 0.005$) and pitch ($F = 4.201$, $p = 0.022$), but not hand proximity ($F = 1.357$, $p = 0.258$). None of the interaction terms were statistically significant. Separate comparisons under laterality revealed that, like Experiment 1, participants' right hand responses were significantly faster than their left hand responses ($p = 0.005$). Separate comparisons under pitch also revealed that, like Experiment 2, participants' responses toward the high tone were significantly faster than those toward the low ($p = 0.051$) and med tones ($p = 0.018$). Finally, and most importantly, we did not observe the critical finding from Experiment 1, namely faster RT for the left hand in auditory localization when hands are within close proximity of the auditory stimuli.

The absence of the nearby-hand effect suggests that the effect is much weaker in the auditory domain, and cannot support auditory processing beyond simple RT tasks. While one could argue that the current task might have been too difficult, or was still not spatial enough to rule out the second hypothesis, we think this is unlikely for several reasons: (1) the localization and discrimination protocol here is identical to those from the first two experiments, (2) we did replicate the general right-hand RT advantage from Experiment 1, suggesting that the current task indeed contained the critical spatial component that was necessary, and (3) we also replicated the high-pitch index-finger advantage from Experiment 2, thus every general effect was replicated except the specific effect of hand proximity. Taken together, we have successfully replicated the right-hand and index-finger RT advantage from Experiments 1 and 2, respectively. These replications of the motor-related effects suggest that the motor programming codes between all three experiments are quite consistent, and therefore the lack of replication of the hand proximity effect is less likely to be attributable to the more complex format of motor response in Experiment 3. Although there is a slightly bigger RT decrease in the left hand when hands are nearby, the magnitude does not reach statistical significance (**Figure 4**). Together, these results support the *insufficient* hypothesis from the previous two experiments, and suggest that hand proximity has a significant but limited effect in altering auditory processing. Consequently, when performing a simpler spatial discrimination task, the (left) hand proximity effect is observed, but when performing a more complex discrimination task, this proximity effect is eliminated.

GENERAL DISCUSSION

The present study was set out to test whether multimodal neurons are likely the neural mechanism underlying the effect of hand proximity in vision (e.g., Reed et al., 2006; Tseng et al., 2012; Brockmole et al., 2013). To this end, we utilized the auditory characteristics of these neurons and tested whether the effect of hand proximity in vision can also be observed in audition. In Experiment 1, we found that binary spatial discrimination became faster for the left hand/side when both hands are near the audio source, providing support for Reed et al.'s (2006) original report of left hand/side RT advantage, as well as their multimodal neuron account for the facilitatory effect. In Experiment 2, using a non-spatial pitch discrimination task that is measured by choice RT, we found no effect of hand proximity, neither facilitation nor impairment. This could be due to the fact that the spatial aspect—an important component for the effect of hand proximity—was taken out with the unidirectional audio setup, or the fact that choice RT was just too complex for the hand effect, at least in the auditory modality (but certainly not in vision). These competing explanations were resolved in Experiment 3, where we reintroduced the binary spatial discrimination element from Experiment 1, together with pitch discrimination, in order to make the pitch choice RT task more spatially relevant: we again found no effect of hand proximity, suggesting that the complex choice-response task was the key to why the hand effect failed to facilitate performance. Together, these results suggest that (1) the effect of hand proximity is not exclusive to vision, but can also enhance auditory processing to certain extent, and (2) the multimodal neuron hypothesis originally provided by Reed et al. (2006) is supported by the current findings, and (3) the effect of hand proximity is weaker in audition than in vision since only auditory-spatial discrimination, but not tone discrimination, is enhanced.

It is important to note that the present findings cannot be explained by stimulus-response compatibility (Simon, 1968; Simon et al., 1970; Lloyd et al., 2010) or the comfort level of the hands. First, in the present study, the left hand was always responding to the left stimulus and the right hand was always responding to the right stimulus (Experiments 1 and 3). The upper fingers always responded to the high tone, the middle finger to the med tone, and the lower finger to the low tone (Experiments 2 and 3). These stimulus-compatible patterns were the only ones used, and stayed the same throughout the entire experiment; thus there were no response configurations that were incompatible with the stimulus. Second, regarding hand comfort, one notable study has already demonstrated that the effect of hand proximity in vision cannot be attributed to the posture or comfort that is associated with the nearby-hand setup (Weidler and Abrams, 2013). But most importantly, if the effect we have observed here was purely driven by easier positioning of the hands, then we should have observed faster RT for the right hand in Experiment 1 and for both hands in Experiment 2, but this was not the case and the facilitatory effect of hand proximity was not only left-hand specific, but also task specific.

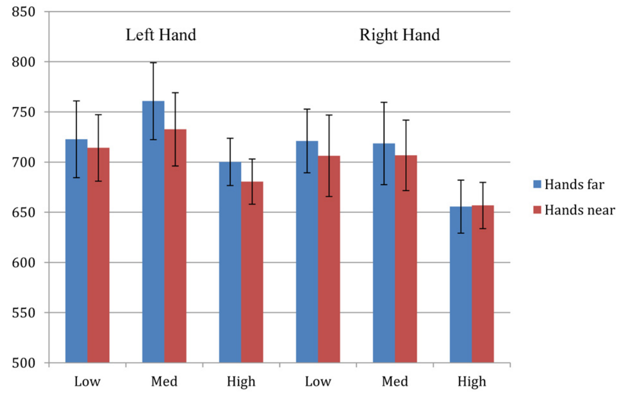

FIGURE 4 | Experiment 3 results. ANOVA revealed a significant main effect of laterality ($F = 10.134$, $p = 0.005$) and pitch ($F = 4.201$, $p = 0.022$), but not hand proximity ($F = 1.357$, $p = 0.258$) or other interaction terms. Separate comparisons under laterality revealed that, like Experiment 1, participants' right hand responses were significantly faster than their left hand responses ($p = 0.005$). Separate comparisons under pitch also revealed that, like Experiment 2, participants' responses toward the high tone were significantly faster than those toward the low ($p = 0.051$) and med tones ($p = 0.018$). Thus, all the general effects from Experiments 1 and 2 are replicated, except the effect of hand proximity.

RIGHT HAND ADVANTAGE IN THE HANDS-AWAY CONDITION

The critical finding from the present study is the improved RT in the left hand when performing auditory binary spatial discrimination (a gross form of localization). A closer examination of **Figure 2** suggests that the right hand was initially faster than the left (hands-far condition), but that difference was no longer present in the hands-near condition due to faster performance in the left hand, rather than slower performance in the right (Experiments 1 and 3). It is curious why, in the default setting (hands away), there may be left vs. right hand asymmetry in RT in the first place. In vision, it has been repeatedly shown that right-handers respond faster with their right hand even when the two hands are crossed (Berlucchi et al., 1971). This is likely because the right hand is very well-rehearsed in all tasks (at least in right-handers), and therefore it is always operating at the ceiling level; such ceiling performance would explain why the right hand could not benefit from hand proximity. Another possibility, though less intuitive, is that perhaps most right-handed individuals are mostly left-hemisphere dominant (Berlucchi et al., 1977), and therefore would respond quicker with their contralateral right hand and slower with their ipsilateral left hand (due to inter-hemispheric transmission). Further research has suggested that although this anatomical lag persists in all kinds of tasks, the magnitude of the lag is clearest in simple RT paradigms, and becomes less clear or even nonexistent in choice RT paradigms due to the additional processes that are involved (e.g., Anzola et al., 1977), accurately reflecting what was observed in the present study. As such, it is also reasonable that our participants (all right-handed) would show a right-hand advantage in tasks requiring auditory spatial discrimination.

THEORETICAL IMPLICATIONS

In the context of a speeded RT paradigm, we think the left-hand improvement possibly implies an increasingly active right hemisphere induced by the hands (see Langerak et al., 2013, for a recent example). A similar idea has been proposed before to explain the effect of hand proximity in vision (Bridgeman and Tseng, 2011; Tseng et al., 2012), because incidentally the right parietal cortex (where the multimodal neurons are) is heavily involved in the process of multisensory integration, and would also provide a consistent account for the current findings. More direct evidence for a right hemisphere involvement comes from a neuroimaging study by Brozzoli et al. (2012). These authors used fMRI to investigate the remapping of hand-centered space while their participants experienced the rubber hand illusion. They found that functionally, the degree of remapping of hand-centered space was strongly correlated with activities in the right posterior parietal cortex, while phenomenologically, the degree of conscious feeling of ownership over the fake hand is correlated with activities in the left premotor cortex. This dissociation between the roles of the right parietal cortex and left premotor cortex is quite informative, and implies that the effect of hand proximity likely recruits the parietal cortex. This explanation is also consistent with all previous reports of the effect of hand proximity in vision, because the right parietal lobe is not only involved in multisensory integration, it is also associated with a multimodal, or supramodal, representation of space and spatial attention (e.g., Farah et al., 1989; Molholm, 2006; Rushworth and Taylor, 2006). Note that, however, here we assume the effect of hand proximity in vision and audition is mediated by a common set of multisensory neurons, or at least different multisensory neurons located within the same brain region. It remains possible that this may not be the case, and an alternative possibility is that visual and auditory modalities exhibit similar laterality effects and are therefore likely to be similarly lateralized in the brain.

Besides the multimodal neuron hypothesis raised by Reed et al. (2006), recently a new hypothesis that suggests the magnocellular pathway as a possible mechanism for the nearby-hand effect has also received much empirical support (Gozli et al., 2012; Abrams and Weidler, 2013; Chan et al., 2013). The parvo/magno hypothesis states that nearby-hands automatically biases the visual system to recruit the magnocellular pathway more, which processes visual information rapidly while sacrificing details such as colors. However, it is unclear how such mechanism in vision can account for the current findings here in audition. In addition, one advantage of the multimodal account is that it is not limited to the stage of perception. That is, although nearby-hands can modulate visual processing early at the perception level (e.g., Brown et al., 2008; Cosman and Vecera, 2010; Gozli et al., 2012), it can also have later effects at the attention level such as semantic judgment (Davoli et al., 2010), attentional shielding (Davoli and Brockmole, 2012), tool functionality processing (Reed et al., 2010), or joint-attention processing (Sun and Thomas, 2013). Perhaps a third alternative is that there may possibly be dual mechanisms for the nearby-hand effect in vision (multisensory plus parvo/magno), but not in audition (multisensory only, without parvo/magno). This idea would explain why the observed effect of hand proximity here is much weaker in audition than vision. Further research is necessary to test whether this dual-mechanism account of hand proximity is feasible or not. Nevertheless, the most important theoretical contribution of the current findings would be the demonstration of the effect of hand proximity on auditory stimuli. This implies that the perceptual and attentional effect of hand proximity is not limited to one specific modality, but applicable to the entire "space" near the hands, including whatever stimuli (at least visual and auditory) within that space. This would also be consistent with the abovementioned supramodal representation of space (Farah et al., 1989).

AN ALTERNATIVE EXPLANATION FOR THE LEFT HAND IMPROVEMENT

Although we favor the right parietal cortex as responsible for the left hand improvement in auditory localization (Tseng et al., 2012), an alternative explanation should also be considered. Specifically, it remains possible that there was no effect of hand proximity in the right hand because the right hand treats both near and far distances as within the peripersonal space. In other words, the extent of the peripersonal space is asymmetrical between the left and right hand, with the right hand enjoying an augmented peripersonal space (Peters and Ivanoff, 1999). Support for this idea comes from studies showing that tool-use can temporarily but effectively augment auditory peripersonal space (Serino et al., 2007), and the right hand's extended training in using computer mouse and keypad makes it possible to shrink the far space into near (Bassolino et al., 2010) because the right hand is used to acting on these near-hand devices while observing the effects of such actions take place in far space (i.e., on the computer screen far away). From this perspective, the effect of hand proximity is actually present in the right hand, both the hands-near and hands-far conditions (Experiment 1) because the far space is effectively treated as near. However, there is one point in our study that goes against this explanation. The original Bassolino et al. study (2010) reported a shrinking far-space in right hands due to mouse usage. This effect is unlikely to transfer to keyboard or keypads in the current study because the left hand, although less adept in using a mouse, is completely adept in using a keyboard since typing requires both hands regardless of one's handedness. Therefore, one would expect a null finding in the left hand in Experiment 1 with equally fast RT as the right hand in both hands-near and hands-far conditions, if extended training on keypad was indeed effective in shrinking the far space.

INCONSISTENT LEFT- AND RIGHT-HAND ADVANTAGE IN THE EFFECT OF HAND PROXIMITY

The current finding of a left hand/side RT improvement is consistent with the finding of Reed et al. (2006), but presents a sharp contrast with the right hand/side advantage reported by Tseng and Bridgeman (2011). Indeed, the kinds of tasks that are used by different studies seem to show different sides of attentional prioritization and bias (for a review, see Tseng et al., 2012). Previously, Tseng and Bridgeman (2011) proposed a functional account that aims to explain the right hand bias as a reflection of the frequency of the uses of each hand (also see Reed et al., 2010, for a similar account in tool-use). In light of our current finding on a left hand improvement, our working hypothesis is that perhaps a simpler detection type of task, such as the speeded localization task from Experiment 1 here and the Posner's paradigm (i.e., detecting visual targets) employed by Reed et al. (2006), especially measured in RT, can be shown in the form of a left hand advantage. The right hand advantage, on the other hand, is likely a result of the top-down influence (e.g., Garza et al., 2013) that prompts observers to attend right (the functional account), as shown by the more complex visual discrimination task (Lloyd et al., 2010) and change detection task (Tseng and Bridgeman, 2011) that requires accuracy and not speed. This hypothesis will need further testing and fine-tuning, and will certainly need to include the interaction between task type and one's handedness, as it has been shown that one's handedness can also change the area of attentional prioritization (Le Bigot and Grosjean, 2012). As previously mentioned, a difference between left- and right-hand ceiling performances may also contribute to whether the effect of hand proximity is observable. Future research is needed to determine whether individual differences in such laterality of the effect is a result of anatomical hemisphere dominance, differential ceiling between the left- and the right-hand, top-down attentional bias that is learned over time (Reed et al., 2010; Tseng and Bridgeman, 2011), or all of the above.

CONCLUSION

In this study, we demonstrate that the effect of hand proximity that is often observed in vision can also be observed in audition when hands are placed near the audio source. Interestingly, this effect is only present in an auditory location discrimination task (simple RT; Experiment 1), and disappears when complex judgment such as pitch discrimination is required (choice RT; Experiments 2 and 3). Furthermore, the facilitative effect only exists in left hand RT. We take these results as evidence supporting Reed et al.'s original multisensory account (2006). We also note that the effect in audition is perhaps weaker than vision, which leaves open the possibility of a dual-mechanism account (multisensory plus magno/parvo) that is exclusive to vision but not audition. The current finding also raises new questions regarding the effect of hand proximity, such as the role of hemispheric difference and top-down attentional bias in initiating the effect, and whether there is a systematic pattern underlying the laterality of the nearby-hand effect, all of which remains to be addressed by future studies.

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How action influences object perception

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Although object perception is typically associated with the parvocellular (P) pathway, a form of fast "gist" object perception may be due to activity in the magnocellular (M) pathway (Kveraga et al., 2007). Because the M-pathway is typically associated with action, we hypothesized that manipulations of action would influence speeded object perception. In three experiments, participants indicated whether the objects shown in low and high spatial frequency (HSF) images were larger or smaller than a prototypical shoebox. In Experiment 1, participants used a proximal (hands on monitor) or distal (hands on keyboard) hand posture in separate blocks. In Experiment 2, only the proximal hand posture was used, but the hands were either action oriented with palms in (palms toward the stimuli) or non-action oriented with palms out (palms away from the stimuli). In Experiment 3, we used the palms-in proximal hand posture but manipulated the type of visual stimuli such that they were either action oriented (easily grasped) or non-action oriented (not easily grasped). In all three experiments, the advantage in identifying the low spatial frequency (LSF) images was greater when action was primed (proximal hands, palms-in, graspable). Together, these experiments show that the M-pathway is involved in rapid "gist" object perception, and this type of object perception is influenced by action.

Keywords: object perception, magnocellular pathway, action perception, visual pathways, near-hand vision, hand-altered vision

HOW ACTION INFLUENCES OBJECT PERCEPTION

One fundamental question regarding visual perception involves what neural streams are responsible for early visual processing. Researchers have discovered that there are two main visual pathways, the Magnocellular pathway (M-pathway) and Parvocellular pathway (P-pathway). Many differences exist between both pathways, with the M-pathway processing information such as motion (Derrington and Lennie, 1984; DeYoe and Van Essen, 1985; Livingstone and Hubel, 1987) and location (Derrington and Lennie, 1984; Chen et al., 2006) and the P-pathway processing information such as color (Derrington and Lennie, 1984) and detailed object features (Maunsell et al., 1990). Thus, broadly speaking, the M-pathway provides visual information related to the planning and production of actions while the P-pathway provides detailed visual information related to the M-pathway (Livingstone and Hubel, 1987; Chen et al., 2006). One noteworthy property of these systems is that they are mutually inhibitory in that when the M-pathway is biased, the P-pathway is inhibited, and vice versa.

Although the P-pathway has traditionally been associated with object perception, Kveraga et al. (2007) have suggested that the M-pathway is also involved in object identification. Their study took advantage of the well-known finding from Wiesel and Hubel (1966) that M-cells are sensitive to low spatial frequency (LSF) information whereas P-cells are sensitive to high spatial frequency (HSF) information. Kveraga et al. presented subjects with line drawings of objects that were either LSF or HSF. The LSF images were all low-luminance and monochromatic, whereas the HSF images were chromatically defined and isoluminant. Subjects were presented with either a LSF or HSF image, and were asked to respond as to whether the object was larger or smaller than a typical shoebox. Results showed a benefit for LSF images. Reaction times (RTs) for LSF images were on average 105 ms faster than HSF images and the overall accuracy of the LSF images were significantly better than the HSF images. Kveraga et al. hypothesized that these findings were due to LSF "gist" information being rapidly carried by the M-pathway to support rapid object perception. This gist image activates predictions about candidate objects similar to the image in their LSF appearance, which are in turn fed back from the frontal lobe to ventral object recognition regions to facilitate distinction among these object candidates.

If the M-pathway is involved in rapid object identification, it follows that processes also supported by the M-pathway might exert some influence on object perception. Specifically, as the M-pathway is thought to underlie the action systems in primates (Wiesel and Hubel, 1966), we examined the role of action on object perception. To accomplish this, we made use of a manipulation of hand posture first reported by Abrams et al. (2008). Across three experiments, Abrams et al. had participants assume either a proximal hand posture (where both hands were up toward the computer screen) or a distal hand posture (where both hands were down toward the keyboard). They found that the proximal hand posture resulted in steeper search slopes, greater inhibition of return (IOR), and increased attentional blinks compared to the distal hand posture. Using the same manipulation, Davoli et al. (2010) presented participants with sensible and nonsensical sentences and found that semantic processing was impoverished near the hands. They also presented participants with a traditional Stroop inference task and found that the magnitude of the effect was dramatically reduced when subjects adopted a proximal hand posture. In addition, Tseng and Bridgeman (2011) found improved change detection performance with hands in proximal position. Thus, hand posture has been found to have a robust effect of a variety of tasks.

In order to explain the constellation of effects resulting from placing both hands on the computer monitor where the stimuli are being presented, Gozli et al. (2012) proposed that a proximal hand posture biased processing in the M-pathway and a distal hand posture biased processing in the P-pathway. In their study, participants completed a spatial gap task in which they estimated varying gap sizes and a temporal gap task in which they estimated varying stimulus onset asynchronies (SOAs). In both conditions, participants assumed either a proximal (hands close to the stimuli, thus priming action) or distal (hands further from the stimuli and not priming action) hand posture. Gozli et al. reported that when participants had a proximal hand posture, they were better at the temporal gap task, as predicted by the higher temporal resolution associated with the M-pathway. When participants assumed a distal hand posture, they were more accurate at the spatial gap task, as predicted by the higher spatial resolution associated with the P-pathway. Thus, this experiment provides the initial evidence different hand postures biases activity in the two visual systems.

Further support for the notion that a proximal hand posture biases M-pathway processing comes from Goodhew et al. (2013) using object substitution masking (OSM). An OSM task involves a sparse (e.g., four dot) temporally-trailing mask obscuring the visibility of a briefly-presented target (c.f. recent review on OSM, Goodhew et al., in press). Treating OSM as a problem of temporally segregating the mask from the target, Goodhew et al. reasoned that if a proximal hand posture biases M-pathway activity and improves temporal resolution, it should reduce the effect of the masks. Across two experiments, this is indeed what they found, providing more evidence that a proximal hand posture biases the M-pathway while a distal hand posture biases the P-pathway. Taken together, the Gozli et al. (2012) and Goodhew et al. (2013, in press) studies indicate that manipulating hand posture is a useful tool to investigate whether actions can influence object perception.

To address the question of whether objects are affected by action, a similar object perception task to that of Kveraga et al. (2007) was used in the three experiments of this study. That is, participants were shown either LSF or HSF images of objects and asked to indicate (either with a keypress or a mouse click) whether the object was larger or smaller than a prototypical shoebox. Different action manipulations, however, were used across the three experiments. The first experiment used the same hand posture manipulation as Abrams et al. (2008) and Gozli et al. (2012); both hands either proximal or distal. Experiment 2 used two variations of the proximal hand posture; palms-in (toward the display) or palms-out (away from the display). The final experiment used a single palms-in proximal hand posture but the type of visual image was manipulated (objects that were either easy or difficult to act on). These three interrelated action manipulations were used to test the idea that the action-based M-pathway is involved in rapid object perception using gist processing.

We hypothesize that anything which primes "action" will in turn bias the M-pathway. According to the hypothesis proposed by Kveraga et al. (2007), the M-pathway is involved in some form of fast object perception, in that the M-pathway quickly uses LSF information to quickly provide a blurred template of an object, which is then filled in by our top-down memories of objects. They coined this "gist" processing, as they argued that the M-pathway just used the "gist" of the information available from the object for speeded object perception. To test this hypothesis, we exploited the fact that the M-pathway is also an action pathway, responsible for processing motion and action. We therefore surmised that priming action would also prime the M-pathway. This priming biases the M-pathway, which in turn biases the processing of "gist" information, and in our case, LSF information.

EXPERIMENT 1

In the first experiment participants either assumed a proximal (hands up) or distal (hands down) hand posture and were instructed to determine if the LSF and HSF images represented objects that were larger or smaller than a prototypical shoebox. Although the task is a relative size judgment task, the task requires participants to correctly identify the object before making an accurate assessment of the size, since the actual stimuli provides little information about the actual size of the object. Therefore, if the proximal hand posture biases M-pathway processing, and rapid gist object perception relies on the M-pathway, we predict that the LSF advantage reported by Kveraga et al. (2007) will be greater with the proximal hand posture than the distal hand posture.

SUBJECTS AND APPARATUS

Twelve University of Toronto undergraduates (mean age = 22.8; 8 females) participated in Experiment 1. Subjects received course credit for their participation. All subjects reported normal or corrected-to-normal vision and none were aware of the hypothesis tested. The experiment was conducted in a dimly lit, sound-attenuated testing room. Visual stimuli were presented on a CRT computer monitor with a refresh rate of 85 Hz. A chin and head rest maintained a viewing distance of 48 cm. Responses were collected on a standard keyboard with a key press ("F" or "J" key).

PROCEDURE AND DESIGN

All stimuli were presented on a gray background. Each trial began with a white fixation cross in the middle of screen for between 250 and 750 ms, to prevent participants from anticipating the onset of the stimulus. Next, a grayscale object (5° × 5°) replaced the fixation cross at the center of the screen. The object was either HSF or LSF created by either a high pass filter, or a Gaussian blur of 5° ($\sigma = 2.5$, 0.027°/cycle), respectively (**Figure 1**). The spatial frequency of the image was randomized across every trial, and each image was shown as both LSF and HSF. Participants were instructed to make a size judgment response by indicating whether the object was larger ("J" key) or smaller ("F" key) than a shoebox. Participants completed this task both with their hands

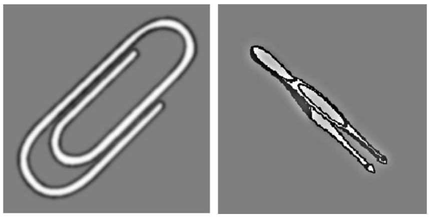

FIGURE 1 | Left: LSF image. **Right:** HSF image.

FIGURE 2 | Left: Distal hand position. **Right**: Proximal hand position.

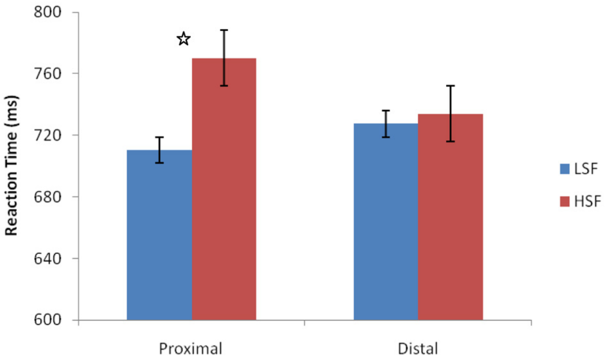

FIGURE 3 | Reaction times for proximal and distal hand postures. No main effect of hand posture or spatial frequency. However, significant interaction between spatial frequency and hand posture. Error bars represent standard errors of means. $^*p < 0.05$.

proximal (hands on the computer monitor) or distal (hands on the keyboard) to the stimuli in counterbalanced blocks of 320 trials each (**Figure 2**). Thus, there were four conditions in total (HSF/hands proximal, HSF/hands distal, LSF/hands proximal, and LSF/hands distal). There were a total of 80 unique images taken from the International Picture-Naming Project (Szekely et al., 2003), each of which was viewed four times across the four conditions. The stimulus set consisted of everyday items (e.g., lamps, backpacks, saltshaker) that were matched for name familiarity, in that previous studies showed no advantage for image naming across all the stimuli (Szekely et al., 2003).

RESULTS AND DISCUSSION

Trials with RTs less than 100 ms or greater than 2 standard deviations from the participants mean RT were removed prior to analysis (less than 2% of all trials). The RTs were analyzed with a repeated measures ANOVA with within-subjects factors of hand posture (proximal or distal) and spatial frequency (LSF or HSF) (**Figure 3**). No main effect of spatial frequency [$F_{(1,\ 11)} = 4.262$, $p = 0.063$, $\eta_p^2 = 0.279$] or hand posture [$F_{(1,\ 11)} = 0.063$, $p = 0.807$, $\eta_p^2 = 0.006$] was found. However, a significant interaction between hand posture and spatial frequency indicated that the LSF advantage was larger when hand posture was proximal rather than distal, [$F_{(1,\ 11)} = 6.377$, $p = 0.028$, l, $\eta_p^2 = 0.367$]. A *post-hoc t*-test demonstrated that when hands were proximal to the stimuli, participants were faster at processing LSF than HSF information [$t_{(11)} = 2.418$, $p = 0.034$, $d = 1.459$], but not when the hands were distal [$t_{(11)} = 0.581$, $p = 0.573$, $d = 0.350$]. The finding that hand posture affected rapid object perception for LSF images supports Kveraga et al.'s (2007) hypothesis that gist processing is performed by the M-pathway.

One result worth noting is that, compared to the distal condition, there seemed to be an increase in RTs for HSF objects in the proximal condition vs. the distal condition, instead of a decrease in RTs for LSF objects. This is most likely due to the mutually inhibitory relationship between the M and P-pathways (Yeshurun and Levy, 2003), as a bias toward the M-pathway also means an inhibitory effect toward the P-pathway, which would tend to increase RT in the distal condition.

EXPERIMENT 2

Although the results from Experiment 1 are consistent with the notion that rapid gist object perception is supported by the M-pathway, an alternative interpretation needs to be considered. Specifically, it may be that by having the hands proximal to the computer screen, people are attending to the stimuli differently because the images are in peripersonal space. In other words, the effect we have found may be due to a change in attention with hand posture, not a bias in action-based M-pathway processing. Indeed, there is evidence to support this alternative. For example, Reed et al. (2006) presented participants with a standard covert attention task, where on each trial, a highly predictive visual cue (70%) indicated the probability of the target appearing at that location. Participants responded when a target appeared at either the cued location (validly cued trial) or the uncued location (invalidly cued trial). Furthermore, participants had their hands placed beside one of the target locations (either to the left or right of the computer screen). Reed et al. reported that participants were faster at responding to valid cues at the locations closer to their hands, suggesting that attention was biased toward hand locations. Therefore, it may be that the findings of our first experiment were driven by increased attention near hand space in the proximal hand condition.

In order to test between the action-based and attention-based possibilities, a second experiment was conducted which only the proximal hand posture was used. In this case, however, we manipulated the direction of the palms, such that the palms were facing toward (palms-in) or away from (palms-out) the object images (**Figure 3**). If the effects found in the first experiment were due to activation of the action-based M-pathway, we would expect to see a greater LSF advantage with palms-in (because the object images are in action space) than with palms-out (because the objects images are out of action space). Our rationale for this is that a palms-in posture will provide a stronger bias of the M-pathway because we typically act on objects with our palms rather than the backs of our hands. If, however, the effects were due to greater attention to the images in the proximal condition, there should be no differences in the LSF advantage between the two condition because the hands are the same distance from the stimuli.

SUBJECTS AND APPARATUS

Fourteen University of Toronto undergraduates (mean age = 18.1; 11 females) participated in Experiment 2. Based on the effect size from the critical interaction in Experiment 1, 14 subjects would achieve 88% power. Subjects received course credit for their participation. All subjects reported normal or corrected-to-normal vision and none were aware of the hypothesis tested. The experiment was conducted in a dimly lit, sound-attenuated testing room. Visual stimuli were presented on a CRT computer monitor with a refresh rate of 85 Hz. A chin and head rest maintained a viewing distance of 48 cm.

PROCEDURE AND DESIGN

The design of the second experiment was the same as Experiment 1 except that two proximal hand postures are used. One hand posture is the palms-in posture, which is identical to the proximal hand posture of Experiment 1. The second hand posture is the palms-out posture, in which participants pointed their palms out away from the computer screen (**Figure 4**). In both these postures, the distance between the stimuli and their hands remained constant. In order to help facilitate comfort in the palms-out posture, pillows were used to brace the arms and elbows, and were also used in the palms-in posture to keep consistent between conditions.

RESULTS AND DISCUSSION

Trials with RTs less than 100 ms or greater than 2 standard deviations from the participants average RT were removed prior to analysis (less than 3% of all trials). The RTs were analyzed with a repeated measures ANOVA with within-subjects factors of hand posture (palms-in or palms-out) and spatial frequency (LSF or HSF). There was a main effect of spatial frequency [$F_{(1,\ 12)} = 12.543$, $p = 0.004$, $\eta_p^2 = 0.491$], with faster RTs for LSF images (**Figure 5**). A main effect of palms was found [$F_{(1,\ 12)} = 8.920$, $p = 0.011$, $\eta_p^2 = 0.663$], with faster responses with palms-in than palms-out. This may have been due to the fact that having palms-in was generally more comfortable for the participants. Importantly, the interaction between palm position and spatial frequency was significant [$F_{(1,\ 12)} = 25.572$, $p = 0.0001$, $\eta_p^2 = 0.663$]. A *post-hoc t*-test confirmed that participants had an advantage at identifying LSF images when their palms were in, [$t_{(13)} = 5.346$, $p = 0.001$, $d = 2.965$], but not when their palms were out [$t_{(13)} = 1.454$, $p = 0.17$, $d = 0.806$]. This interaction, driven by the shorter RTs for the LSF images in the palms-in hand posture, provides strong evidence that priming action does indeed influence object perception. Thus, these data provide additional support to the idea that priming action biases the M-pathway, which allows our visual system to prioritize LSF information.

FIGURE 4 | Left: Palms-in hand posture. **Right:** Palms-out hand posture.

EXPERIMENT 3

The findings of the first two experiments converge to suggest that action, as manipulated through hand position, can alter object perception via the M-pathway. In our last experiment, our aim was to confirm this interpretation by using a paradigm that required only a single hand position. In Experiment 2, it may be the case that because of the nature of the palm orientation, there are still attentional effects at play. Indeed, Reed et al. (2010) proposed that a larger number of bimodal neurons represent our palms than the back of our hands, which allows for greater attention near the palms. Therefore, in the present experiment, we used a single proximal hand posture but this time manipulated action through the stimuli being presented. It can be reasoned that if priming action induces a bias toward the M-pathway, then stimuli that are "action oriented" should yield similar results to the first two experiments (i.e., faster responses for LSF action-oriented images). In our world, there are many objects that are more easily associated with action, such as objects that are graspable or easily manipulated with our hands. It would stand to reason that these objects would produce an effect of action, as opposed to objects that are harder to manipulate with our hands. Therefore, our third experiment used objects that were either easily graspable or easily manipulated with the hands (action-oriented) or

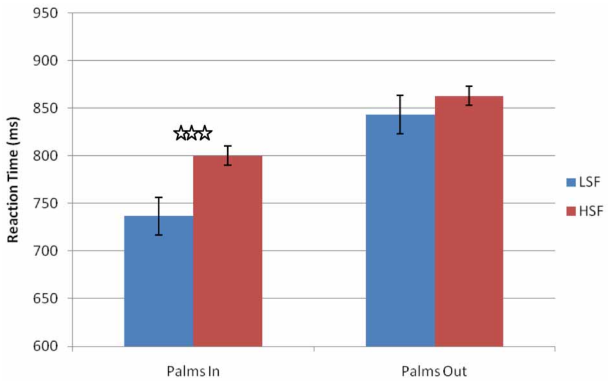

FIGURE 5 | Results from Experiment 2. Main effect of spatial frequency and significant interaction between spatial frequency and hand posture. Error bars represent standard error of means. $^{***}p < 0.001$.

objects that were not (non-action oriented) in order to bias the M-pathway without changing hand posture (**Figure 5**).

SUBJECTS AND APPARATUS

Eight University of Toronto undergraduates (mean age = 19.75; 2 females) participated in Experiment 3. Based on the mean effect size of the critical interaction in Experiments 1 and 2, this achieved 82% power. Subjects received course credit for their participation. All subjects reported normal or corrected-to-normal vision and none were aware of the hypothesis tested. The experiment was conducted in a dimly lit, sound-attenuated testing room. Visual stimuli were presented on a CRT computer monitor with a refresh rate of 85 Hz. A chin and head rest maintained a viewing distance of 48 cm.

PROCEDURE AND DESIGN

The design of the third experiment was the same as that of Experiment 1 except for two differences. First, only the proximal hand posture (with palms facing in) was used. Second, the stimuli were changed to match two categories: action-oriented objects and non-action oriented objects. Action oriented objects were objects such as tools that met two criteria. The first was that the object had to elicit a natural action that is performed by the hands. The second is that the action done by the hands had to accomplish a goal or a task. For example, a dustpan is an object that elicits an action from the hands (grasping it and moving it), while doing so accomplishes a goal (picking up dust) (**Figure 6**). Non-action oriented objects were objects that did not meet these 2 requirements (e.g., a door hinge as in **Figure 6**). Forty unique objects were used in Experiment 3 and all objects were matched for image size. All objects were taken from the same naming database as Experiment 1. The task and responses also remained the same as Experiment 1. Experiment 3 consisted of 160 trials with action and non-action oriented objects randomly intermixed, with each item being presented as both LSF and HSF.

RESULTS AND DISCUSSION

Trials with RTs less than 100 ms or greater than 2 standard deviations from the participants average RT were removed prior to analysis (less than 1% of all trials). The RTs were analyzed with a repeated measures ANOVA with within-subject factors of stimulus type (action or non-action) and spatial frequency (LSF or HSF) (**Figure 7**). There was no main effect of object type [$F_{(1,\,7)} = 3.134$, $p = 0.122$, $\eta_p^2 = 0.139$]. But we found a main effect of spatial frequency [$F_{(1,\,7)} = 17.866$, $p = 0.004$, $\eta_p^2 = 0.718$], indicating that LSF images were processed faster. Furthermore, we found a significant interaction between object type and spatial frequency [$F_{(1,\,7)} = 9.560$, $p < 0.018$, $\eta_p^2 = 0.577$], driven by faster RTs to LSF than HSF images when they were "action-oriented" [$t_{(7)} = 5.508$, $p = 0.001$, $d = 4.164$], not when they were "non-action oriented" [$t_{(7)} = 2.478$, $p = 0.071$, $d = 1.873$]. (The marginal difference between the LSF and HSF conditions with non-action oriented objects may have been driven by the palms in posture that was assumed in Experiment 3, which we know from Experiment 2 biases the M-pathway.) Again, these data suggest that participants were faster at processing LSF information when action was primed through the stimulus type. By holding the hand posture constant, we were able to demonstrate that action priming still biases the M-pathway, which allows the visual system to prioritize LSF information.

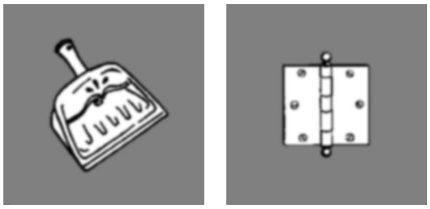

FIGURE 6 | Left: Example of LSF action-oriented object. **Right**: Example of LSF non-action-oriented object.

GENERAL DISCUSSION

The main question that we addressed in these experiments was whether or not action influences object perception. This question arose from Kveraga et al.'s (2007) hypothesis that rapid object perception in accomplished by the M-pathway. In three experiments, we manipulated action in different ways to provide a clear answer: object perception is affected by hand posture, an action-based manipulation that influences M-pathway processing. The first two experiments showed that the LSF advantage (an index of M-pathway processing) was greater with the proximal hand posture (Experiment 1) and with the palms-in posture (Experiment 2), hand postures that prime action and are therefore expected to prime the M-pathway. Experiment 3 showed that the type of images—whether they were action-oriented or not—could also facilitated the LSF advantage, while hand posture was held constant. Thus, the present results show that priming the M-pathway by priming action can indeed influence object perception.

This study provides support for the hypothesis proposed by Kveraga et al. (2007) that the M-pathway is involved in some form of object perception. It seems likely that this M-pathway involvement is in rapid object perception, which allows the visual system to make quick decisions based on limited LSF information, which is a capability that serves an evolutionary benefit.

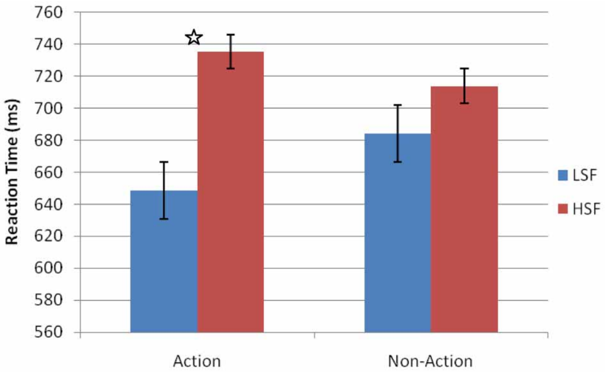

FIGURE 7 | Results for Experiment 3. Main effect of spatial frequency and significant interaction between stimulus type and spatial frequency. Error bars represent standard error of means. $^{*}p < 0.05$.

The M-pathway receives the majority of its input from the rod cells in the retina, which make up most of our field of view. Being able to quickly extract sufficient information about objects in the periphery (predators and prey, edible and non-edible, for example) would be a useful aid in survival. Indeed, when perceiving whether objects may harm or can be manipulated in useful actions, it is not completely necessary to process fine spatial detail, but rather the gist of the object shape allows us to determine its relevance to us. Therefore, priming the M-pathway facilitates speeded object recognitions that allow fast and informed decisions – capacities that would have conferred survival benefits.

Beyond implications for object perception, this research also provides insight into the hand posture literature. The present experiments offers further evidence that the M-pathway drives the effects observed when proximal hand postures are adopted. The increased temporal resolution and the biases toward specific types of information are consistent with facilitation of the M-pathway through the use of action. For example, Gozli et al. (2012) found superior temporal resolution, a characteristic of M-pathway processing, when participants assumed a proximal hand posture. This again could be seen as an evolutionary tool, as the ability to process action-oriented information at an increased speed would have considerable survival value.

Finally, one implication of this line of research is that there might not be a "neutral posture" from which to examine various aspects of perception or cognition. Since the inception of Cognitive Psychology, experiments have been conducted in a sitting posture with participants' hands proximal to the device they must use to make responses (e.g., keyboard, response box, pen and paper). The tacit assumption has been that this posture would produce effects similar to any other posture, or at least be neutral in terms of any specific influences on the task at hand. In fact, this posture appears to bias P-pathway processing, thus potentially altering performance. Thus, it may be useful to re-examine perceptual and cognitive studies that involve potential trade-offs between the M- and P-pathways. However, one thing to note is that in our experiments, we were able to replicate the LSF advantage reported by Kveraga et al. (2007) only when we primed the M-pathway, either by palm positions (Experiments 1 and 2) or by the use of action-oriented objects combined with a favorable palm position (Experiment 3). Perhaps it is necessary to strongly bias the M-pathway processing in order to see the LSF vs. HSF differences. Consistent with this possibility, Kveraga et al. (2007) combined the presence vs. absence of luminance differences with LSF and HSF images. Since we know that the luminance also drives the M-pathway, it might be the case that only under strong biases do we see this fast processing of the M-pathway. Therefore, this observation raises a question regarding the extent to which fast processing in the M-pathway facilitates perception under normal conditions, and whether only under strong biases does the M-pathway provide these observational advantages for LSF information.

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Hand proximity differentially affects visual working memory for color and orientation in a binding task

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Observers determined whether two sequentially presented arrays of six lines were the same or different. Differences, when present, involved either a swap in the color of two lines or a swap in the orientation of two lines. Thus, accurate change detection required the binding of color and orientation information for each line within visual working memory. Holding viewing distance constant, the proximity of the arrays to the hands was manipulated. Placing the hands near the to-be-remembered array decreased participants' ability to remember color information, but increased their ability to remember orientation information. This pair of results indicates that hand proximity differentially affects the processing of various types of visual information, a conclusion broadly consistent with functional and anatomical differences in the magnocellular and parvocellular pathways. It further indicates that hand proximity affects the likelihood that various object features will be encoded into integrated object files.

Keywords: visual working memory, hand posture, binding, color, orientation

HAND PROXIMITY DIFFERENTIALLY AFFECTS WORKING MEMORY FOR COLOR AND SHAPE

The mental processing of the visual world is not independent of our physical interactions within it. A growing literature indicates that our visual experiences reflect a blending of information sensed by the eyes and motor information related to the planning and execution of various physical interactions with objects. For example, softball players who are hitting well see a bigger ball compared to those hitting poorly (Witt and Proffitt, 2005), and tennis players who return more serves successfully see the ball to be moving slower (Witt and Sugovic, 2010; see Witt, 2011 for a review). Although such group differences emerge when considering performance skill, many changes in vision can be induced within individuals by simply altering their ability to interact with objects. For example, recent studies have shown that several aspects of visual cognition are influenced by the proximity with which people hold their hands to objects being inspected (see Brockmole et al., 2013 for a review).

The links between mental processes and hand manipulations are pervasive and are observed at multiple levels of cognition. At a perceptual level, placing the hands near an object can improve visual sensitivity (Schendel and Robertson, 2004) and precision (Vishton et al., 2007). Enhancements have also been observed in one's ability to segregate objects and backgrounds (Cosman and Vecera, 2010), to parse temporally contiguous visual events (Goodhew et al., 2013), and to recognize objects (Adam et al., 2012) near the hands. In terms of attention, objects near the hands receive attentional priority in comparison to objects located elsewhere (Reed et al., 2006, 2010; Davoli and Brockmole, 2012). Shifts of attention are also affected as attentional disengagement from items near the hands is inhibited (Abrams et al., 2008; Davoli et al., 2012a). These perceptual and attentional changes near the hands have been linked to changes in the quality of higher cognitive systems. For example, when the hands are placed near to-be-remembered objects, working memory capacity increases (Tseng and Bridgeman, 2011) and long-term memory for visual details improves (Davoli et al., 2012b). Importantly, these effects of hand proximity are not associated with possible changes in effort, comfort, response location, or hand-visibility that emerge when one places his or her hands near visual stimuli (Reed et al., 2006; Abrams et al., 2008; Davoli and Abrams, 2009; Davoli et al., 2010). Instead, we have hypothesized that these changes in memory occur because enhanced perception, focused attention, and a focus on detail allow for better processing of object properties in a region of space that has great behavioral importance (Brockmole et al., 2013).

Although the studies reviewed above catalog a variety of behavioral changes that occur near the hands, much less work has concentrated on the exact mechanisms by which they arise. One recent hypothesis links the effects of hand position to differential visual processes associated with the magnocellular and parvocellular pathways (Gozli et al., 2012; Goodhew et al., 2013, 2014). These pathways are first differentiated at the level of the retinal ganglion cells, project to different layers of the lateral geniculate nucleus, and terminate in distinct areas of visual cortex. Functionally, the parvocellular pathway processes information such as color and fine spatial details while the magnocellular pathway analyzes low-spatial frequency motion and other dynamic aspects of the world. This anatomical distinction is therefore related to a differentiation between the visual perception of form and the visual coordination of action. According to recent work, placing the hands near an object may in some sense "ready" the visual system for the processing of visually guided actions, leading to a shift, or bias, toward magnocellular processing and away from parvocellular processing. Consistent with this view, Gozli and colleagues showed that when objects appeared near the hands, detection of temporal discontinuities in object presence (a magnocellular process) improved while spatial discontinuities in object contour (a parvocellular process) diminished.

The magno/parvocellular hypothesis suggests that the effect of hand placement on object processing is nuanced, and depends on the nature of the object properties tested. The goal of the current research was to further test this account. We engaged observers in a change detection task in which they were to determine whether two sequentially presented arrays of various colored and oriented lines were the same or different. When changes were introduced, they involved either a shift in color information or a shift in orientation information. Critically, observers did not know in advance which feature might change. Hence, this task required them to memorize all aspects of the first display and to then compare the resulting visual working memory representation with a new percept. Because performance depends on the quality and contents of visual working memory (Luck and Vogel, 1997), this procedure can reveal whether one feature has representational priority over the other when hand placement is manipulated. This approach has three relative advantages over prior work. First, our method uses the same task to differentiate possible processing differences between visual features. Hence, across-task comparisons are unnecessary. Second, by randomly intermixing trial types, it becomes difficult to employ specific and different strategies on a task-by-task or even trial-by-trial basis. Third, and more importantly, our approach allows us to ask additional theoretical questions. Specifically, we can investigate whether hand posture affects one's ability to bind visual features. Because vision acts much like a prism, splitting the processing of features such as form and color into distinct neural networks, some mechanism must reintegrate, or "bind," these features to create a unified representation of the objects in the visual field (see Brockmole and Franconeri, 2009 for a review). If hand position differentially affects the processing of different feature categories, then it may also affect the quality of the resulting object-level representation, as some features would be better represented than others when object files are generated.

Our choice to contrast color and orientation derives from two assumptions. First, color and orientation represent distinct components of visual working memory that are each underscored by unique consolidation processes. For example, the colors of multiple objects can be consolidated in parallel (Mance et al., 2012), while the consolidation of orientation is severely limited in capacity (Woodman and Vogel, 2008; see also Stevanovski and Jolicœur, 2011; Becker et al., 2013). As such, memory for each feature may be differentially impacted by various manipulations of attentional control (in this case hand position). Second, color information is processed by the parvocellular pathway while low spatial frequency orientation information is processed by the magnocellular pathway, and, color is less relevant for potential actions (such as grasping) than is orientation. Thus, if placing the hands near an object leads to a bias in magnocellular and/or action-related processing, changes to object orientations should be best detected when objects appear near the hands while changes to object colors should be best detected when objects appear far from the hands. Alternatively, if hand proximity leads to a universal bias toward object details (cf., Davoli et al., 2012b), both color and orientation memory should be best when the stimuli appear near the hands.

MATERIALS AND METHODS

PARTICIPANTS

Sixty-one undergraduate students participated in exchange for course credit or monetary compensation. Three additional participants were excluded for having false alarm rates equal to or greater than hit rates. Method of remuneration did not predict performance patterns.

STIMULI AND APPARATUS

Stimuli consisted of arrays of six lines presented on a uniform gray background. Each line measured 3 cm in length and 0.7 cm in width. The placement of each line within the array was determined by randomly selecting locations within an imaginary four by four rectangular grid. Each grid space measured 4.75 cm by 4 cm, yielding a maximum display area of 19 cm by 16 cm. The color and orientation of each line was randomly chosen. Possible colors were blue ($L^* = 27$, $a^* = 61$ $b^* = -101$), green ($L^* = 53$, $a^* = -52$ $b^* = 49$), purple ($L^* = 34$, $a^* = 61$ $b^* = -41$), and red ($L^* = 45$, $a^* = 69$ $b^* = 60$). Possible orientations were vertical, horizontal, 45° leftward slant, and 45° rightward slant. Arrays were presented on a 17 LCD monitor with a screen refresh rate of 120 Hz. Responses were made by pressing one of two response buttons. In separate conditions (described below), these buttons were affixed to either the sides of the monitor or to the table in front of the participant. Observers were seated in a stiff-backed (non-reclining) stationary chair that was placed in such as manner as to provide a constant viewing distance of approximately 40 cm with each hand position.

DESIGN AND PROCEDURE

On each trial, participants viewed two arrays of lines (see **Figure 1**). The study array was first presented for 1 s which was followed by a 1 s retention interval during which the screen remained blank. A second test array was then presented. The test array was either identical to the study array (**Figure 1**, top row) or incorporated changes to either the colors or orientations of the lines. On color-change trials, the colors of two randomly selected lines were swapped. For example, a study array containing a red vertical line and a blue horizontal line (**Figure 1**, middle row) could be followed by a test array that contains blue vertical and red horizontal lines (the other four lines would be unchanged from study to test). On orientation change trials, the orientations of two randomly selected lines were swapped. For example, a study array containing a green vertical line and a red horizontal line (**Figure 1**, bottom row) might be changed to include a green horizontal line and a red vertical line at test. Inducing changes to the display in this manner required observers to remember specific combinations of color, orientation, and location, rather than independent features (Wheeler and Treisman, 2002). Articulatory suppression was used throughout each trial to prevent the participants from encoding or rehearsing the stimuli verbally. At the start of each trial, two randomly selected digits were presented that the participant repeated out loud until he or she registered the change detection response.

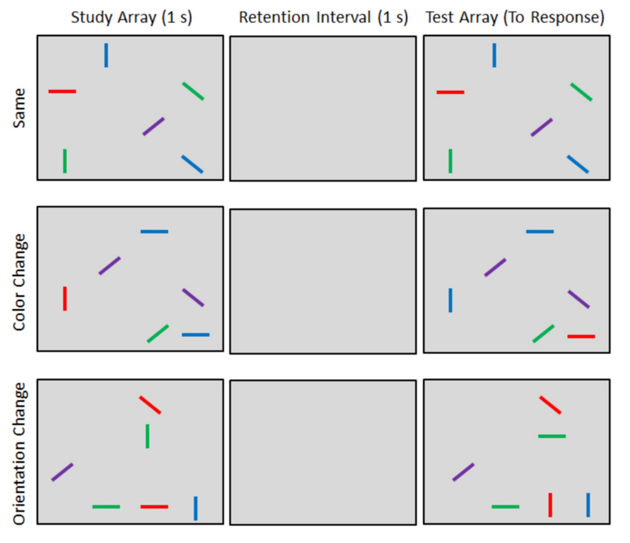

FIGURE 1 | Example stimuli and trials types. Participants indicated whether the study and test arrays were the same or different.

Participants completed two blocks of 160 trials each. Within each block, 80 same trials, 40 color-change trials, and 40 orientation change trials were randomly intermixed. Across blocks, hand position was manipulated. In the hands-far block, participants placed their hands on the table top in front of them. In the hands-near block, participants' hands were placed on the side of the monitor with their elbows resting comfortably on a cushion. In both cases, the hands remained in a stationary position (i.e., observers could not use their fingers as a mnemonic cue to store trial-by-trial information about line orientations). The order of these blocks was counterbalanced across participants. Hence, trial type (same, color-change, and orientation change) and hand position (near and far) constituted within-subjects factors.

RESULTS

RESPONSE TIME

Although the primary analyses of interest concerned accuracy, we submitted response times to a 2 (hand position: near or far) × 3 (trial type: same, color change, or orientation change) repeated measures analysis of variance. Neither the main effect of hand position [$F(2,60) < 1$] nor change type [$F(2,60) = 1.38$, $p = 0.26$] were reliable. Furthermore, these factors did not interact [$F(2,60) = 1.78$, $p = 0.17$]. This ensures that any observed effects in memory accuracy are not due to speed-accuracy trade-offs. Average response time was 1240 ms.

ACCURACY

Responses were classified as hits (correct detection of a change) and false alarms. Hit rates and false alarm rates were then contrasted used a signal detection approach. Hence, d' served as the principle measure of memory performance. Performance was analyzed in terms of a 2 (hand position: near or far) × 2 (change type: color or orientation) repeated measures analysis of variance (see **Figure 2**).

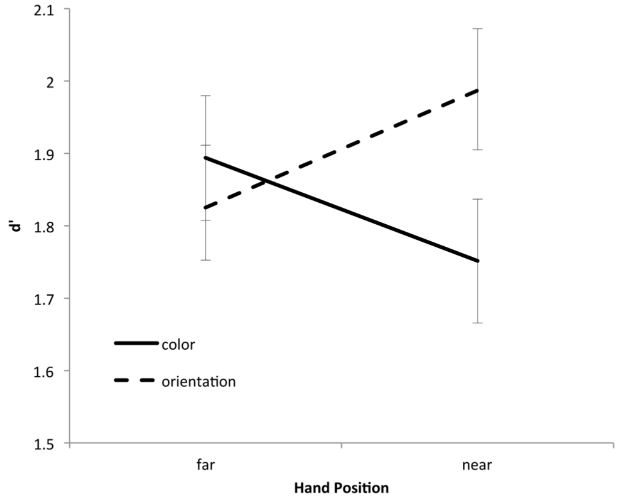

FIGURE 2 | Change detection performance as a function of hand position and change type.

The main effects of hand position [$F(1,60) = 1.75$, $p = 0.19$] and change type [$F(1,60) < 1$] were not reliable. Importantly, however, these factors interacted [$F(1,60) = 16.5$, $p < 0.001$]. Planned comparisons showed that when the hands were far from the monitor, equal levels of performance were observed for color ($M = 1.91$) and orientation ($M = 1.86$) changes [$t(60) < 1$]. When the hands were near the monitor, however, orientation changes ($M = 1.96$) were detected better than color changes [$M = 1.73$; $t(60) = 3.04$, $p < 0.01$]. Moreover, color changes were best detected in the hands-far condition [$t(60) = 2.05$, $p < 0.05$] while orientation changes were best detected in the hands-near condition [$t(60) = 2.18$, $p < 0.05$]. Hence, placing the hands near a set of to-be-remembered objects decreases one's ability to remember color information, but increases his or her ability to remember orientation information.

DISCUSSION

This research considered how working memory for visual objects, defined as coherent sets of visual features (i.e., color and orientation), are maintained as a function of those objects' proximity to the hands during viewing. Our results indicate that color memory is better when the hands are far from to-be-remembered objects while orientation memory is better when the hands are placed near those objects. This result has several implications for conceptions of the interactions between hand placement and vision as well as the structure of visual working memory itself.

Several aspects of visual perception, attention, and memory are influenced by the proximity with which people hold their hands to the objects being inspected (see Brockmole et al., 2013). Previously, we argued that these changes in cognition are adaptive as enhancements in perception, attention, and detail-oriented processing would allow for better object processing in a critical region of space near the body. Recent work, however, has suggested that these benefits may not extend to all object properties, and that the influence of hand position depends upon an anatomical distinction between the magnocellular and parvocellular visual pathways (Gozli et al., 2012; Goodhew et al., 2013, 2014). Our results support this hypothesis. If hand proximity universally affects the processing of all object features, both color and orientation memory should have been best in the near-hand condition. Instead, as the hands approached the objects, orientation processing (a magnocellular process) improved while color processing (a parvocellular process) declined. Thus, our work compliments and extends prior demonstrations supporting a magnocellular—parvocellular distinction in this arena. Our work also does so using a method in which stimulus structure and experimental task remain constant, providing important verification that prior results are unlikely to have arisen from the application of different strategies or experimenter-induced demands within different experimental tasks. So why then do these changes take place as they do? Like others, we suggest that the changes remain adaptive, but are perhaps targeted at visual information/processes most likely to be involved in the planning and execution of action.

Despite the consistency of our results with prior work noted above, our findings do provide a stark departure from some other work. Specifically, some researchers have found that placing the hands near objects increases working memory capacity – and they did so in a task where color served as the to-be-remembered feature (Tseng and Bridgeman, 2011). This is the opposite pattern from what we observed in our study. The reason for this discrepancy is not entirely clear, but differences in methodology might be important. Where improvements in color memory were observed, color was the only feature that needed to be encoded and remembered (all stimuli were colored squares). In our study, however, two features needed to be encoded and remembered (stimuli were colored lines of differing orientation). These two features may compete for processing resources [e.g., the consolidation of orientation is more severely limited in terms of capacity than is color (Becker et al., 2013), leading to a potential processing bottleneck when both features are task-relevant] and hand proximity may play a larger role in object representation under such circumstances. More work will need to be done to explore this possibility, but at a minimum the distinction suggests that a pure dissociation between magnocellular and parvocellular processing is unlikely to be an adequate explanation for hand proximity effects, at least as currently conceived.

Finally, our results shed new light on visual working memory representations when multiple features need to be bound. In order to remember the color and orientation of each line, these visual features needed to be individually processed and then bound together in memory. Our results indicate that object representations arising from these processes are sensitive to extra-perceptual factors such as hand position. When the hands were held far away from the stimuli, color, and orientation information were remembered equally well. However, when the hands were placed near the objects, color memory declined while orientation memory improved. Because both color and orientation needed to be retained on each trial, this suggests that binding in the hands-near condition was disrupted: Observers were no longer able to remember both color and shape, but were instead much more likely to retain orientation information in memory. Whether this disruption occurs early in visual processing (e.g., during stimulus encoding), represents a disturbance in reentrant processing from higher attentional processing areas (cf. Braet and Humphreys, 2009), or occurs during memory consolidation, retention, and/or retrieval remains an important question for future research.

In conclusion, we have shown that hand proximity differentially affects one's ability to remember color and orientation information in a binding task. This result is broadly consistent with the hypothesis that magnocellular and parvocellular processes are differentially affected by hand placement, although other mechanisms likely contribute to the observed effects. The manner in which the representation of objects and their features in visual working memory is affected by extra-visual factors such as hand placement warrants further examination.

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Dissociating between object affordances and spatial compatibility effects using early response components

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Perception and action are tightly linked: objects may be perceived not only in terms of visual features, but also in terms of possibilities for action. Previous studies showed that when a centrally located object has a salient graspable feature (e.g., a handle), it facilitates motor responses corresponding with the feature's position. However, such so-called affordance effects have been criticized as resulting from spatial compatibility effects, due to the visual asymmetry created by the graspable feature, irrespective of any affordances. In order to dissociate between affordance and spatial compatibility effects, we asked participants to perform a simple reaction-time task to typically graspable and non-graspable objects with similar visual features (e.g., lollipop and stop sign). Responses were measured using either electromyography (EMG) on proximal arm muscles during reaching-like movements, or with finger key-presses. In both EMG and button press measurements, participants responded faster when the object was either presented in the same location as the responding hand, or was affordable, resulting in significant and independent spatial compatibility and affordance effects, but no interaction. Furthermore, while the spatial compatibility effect was present from the earliest stages of movement preparation and throughout the different stages of movement execution, the affordance effect was restricted to the early stages of movement execution. Finally, we tested a small group of unilateral arm amputees using EMG, and found residual spatial compatibility but no affordance, suggesting that spatial compatibility effects do not necessarily rely on individuals' available affordances. Our results show dissociation between affordance and spatial compatibility effects, and suggest that rather than evoking the specific motor action most suitable for interaction with the viewed object, graspable objects prompt the motor system in a general, body-part independent fashion.

Keywords: affordance, amputees, EMG, hand, stimulus-response

INTRODUCTION

The idea that an object is perceived not only by its visual features, but also by the potential motor actions it affords (object affordances) has captured the attention and imagination of both scientists (e.g., Tucker and Ellis, 1998, 2004) and philosophers (Gibson, 1979). In support of this notion, a series of behavioral studies have shown that when a centrally located object has a salient graspable feature (e.g., a handle), it facilitates motor responses corresponding with the feature position (the "affordance effect"; Tucker and Ellis, 1998): When participants were asked to perform simple key-press responses with both hands, the response time of the hand most suited to perform a reach-and-grasp movement toward the object handle was speeded. Importantly, affordance effects occurred even when the objects themselves were irrelevant to the task performed by the participants (Phillips and Ward, 2002). Furthermore, objects that facilitate different kinds of grasping (e.g., power grip or precision grip), prime different motor actions accordingly ("micro affordances"; Ellis and Tucker, 2000; Tucker and Ellis, 2004). This line of evidence led researchers to conclude that object affordances automatically activate codes for actions appropriate for the utilization of that object, even when these responses are irrelevant.

However, it might be argued that the object's graspable feature draws attention to that location, thus facilitating responses made by the corresponding hand through a general spatial compatibility effect (Simon and Rudell, 1967). In recent years a controversy has developed around whether the affordance effect is a special case of spatial compatibility, or is in fact dissociated from stimulus-response compatibility effects. A few studies have tried to tease apart the two phenomena, with mixed results. For example Symes et al. (2005) simultaneously manipulated the spatial location of objects and the orientation of their handles, and found that each produced a distinct compatibility effect. These results were taken as an indication that affordance effects and the Simon effect are independent (see also Riggio et al., 2008; Pellicano et al., 2010). However, it is still possible that these results reflected two orthogonal compatibility effects. A similar confound may exist for micro-affordances, which have not been tested against non-graspable objects with similar shapes and sizes.

Other studies have found a tight link between the affordance and spatial compatibility effects (Anderson et al., 2002; Cho and Proctor, 2010; Kostov and Janyan, 2012). Anderson et al. (2002) compared speeded responses to drawings of graspable (scissors) and non-graspable (clocks) objects. They found that the fastest responses tended to arise on the side of the salient feature (handles or dials, respectively) regardless of the afforded motor actions on the object. They therefore concluded that the visual asymmetry of the target object creates an attentional shift leading to the affordance effect. One potential shortcoming of this study is that the authors used schematic line drawings that would not necessarily activate a motor response. As the affordance effect is theorized to be driven by an automatic and ecological motor response, there is a need to measure it with more naturalistic stimuli. Moreover, most experimental paradigms so far have not accounted for differences in salient asymmetrical visual features (e.g., handles) between experimental conditions.

In the present work, we used electromyography (EMG) to study early response patterns emerging in the proximal muscles of the arm during reaching-like movements cued by object images. The use of EMG provides an opportunity to gain insight into the temporal patterns associated with stimulus-response effects, by measuring the timing of different aspects of the movement, particularly the early and late components of muscle responses. In a second experiment, we applied the same experimental design using button-press responses. To dissociate spatial compatibility effects, affordance effects, and to assess their potential interaction, we had participants respond to images of typically graspable and non-graspable objects, presented either on the same or the opposite side to their responding limb. Each graspable object image was paired with a non-graspable object with similar asymmetry, thus accounting for the potential saliency of the handle. If graspable object images facilitate the motor system irrespective of spatial compatibility, then we should find a significant affordance effect (faster reaction times for graspable objects than for non-graspable objects) even while accounting for similarity in object asymmetry and position across conditions. Furthermore, if the affordance effect facilitates a specific motor action, we would expect a larger affordance effect when the object image appears on the same side as the hand most suitable to perform the grasping movement afforded by the object, reflected in an interaction between spatial compatibility and affordance.

A different approach that could help tease apart the potential action component from the perceptual one is that of testing affordance and spatial compatibility effects in populations with altered motor abilities. Unilateral arm amputees are a particularly interesting population in this context, as their disability results in lateralized limb-use, leading to spatially-asymmetrical interactions with objects in their environment. Indeed, we have recently shown that amputees exhibit distorted visuospatial representation of near space, such that they tend to over-represent distances on their intact side, compared to their amputated side (Makin et al., 2010). Based on this finding, we might expect to find modulated spatial compatibility and manipulability effects. By contrast, we have recently demonstrated a maintained representation of the phantom hand in the sensorimotor cortex of (acquired) amputees, as found during volitional phantom hand movements (Makin et al., 2013). This finding may suggest preserved stimulus-response compatibilities in amputees. To examine these hypotheses we conducted a third experiment where we recorded EMG measures during reaching-like movements in a group of individuals with a unilateral upper limb absence (here called "amputees"). This population also allowed us to explore the importance of recent interactions with objects on both affordance and spatial compatibility effects.

METHODS

PARTICIPANTS

A total of 22 intact participants were recruited to the study. Ten participants took part in the EMG experiment (mean ± SD age 27 ± 4 years, all right handed). A total of 18 participants took part in the button press experiment (mean ± SD age 25 ± 3 years, 15 right handed), of whom 6 participated in the EMG experiment prior to the button press experiment. In addition, nine participants with upper limb amputation (mean ± SD age 44 ± 4 years, 4 with absent left hand, 4 with congenital deficiency, as determined by self-report, see **Table 1**) participated in a further EMG study. The handedness of intact participants was assessed using the 20-item version of the Edinburgh questionnaire (Oldfield, 1971). All procedures were approved by the Hadassah Medical Center Ethics Committee, and participants gave written informed consent prior to the experimental sessions.

STIMULI AND EXPERIMENTAL DESIGN

Stimuli consisted of 24 color pictures of everyday objects. The pictures were of typically graspable and non-graspable objects. Each graspable image had a matching non-graspable counterpart with similar visual features and size (see **Figure 1A**). Half of both the graspable and non-graspable objects contained metal. The experiment was conducted in a darkened room. Stimuli were controlled using the Presentation® software (Neurobehavioral Systems, Inc.) and projected on a large screen (163 × 203 cm), such that the image size was about 20 × 20 cm. The images appeared on either the left or the right lower side of the screen (28 cm from the center), at the subject's shoulder height. Trials were presented in a randomized order to avoid order related biases. Each image was presented for 300 ms, with 1700 ms intervals between trials, giving a total of 2000 ms for each trial. The graspable feature (e.g., the handle), or its visual homologue in non-graspable objects, always corresponded to the side of presentation (i.e., when the cup appeared on the right side its handle was oriented to the right as well).

Participants sat 50 cm in front of the center of the screen, within reaching distance, and were asked to keep their gaze on a red fixation cross, which appeared throughout the experiment. The participants performed a task relating to a stimulus feature unrelated to the graspability of the object—they were required to determine whether the object presented contained metal or not, by performing a speeded discrimination response with their left and right hands or arms (see **Figure 1B**). This task was chosen

Table 1 | Detailed information on amputee participants.

Amputee	Age	Years since amp.	Amp. hand (dominant hand?)	Amp. degree	Prosthetic/ Frequency of use (0–5)	Phantom pain	Phantom limb sensation	Comp effect size (ms)	Afford effect size (ms)
A01	31	31 (cong)	L(n/a)	Below elbow	Functional/4	Never	Never	−10.4	6.5
A02	50	50 (cong)	R(n/a)	Below elbow	Functional/4	Never	Never	6.8	−61.6
A03	40	18	L(No)	Below elbow	Cosmetic/5	Daily	Daily	−9.1	−38.8
A04	44	44 (cong)	R(n/a)	Below elbow	Cosmetic/4	Never	Never	25.7	8.1
A05	58	39	R(No)	Above elbow	Mechanic/5	Often	Daily	82.5	−38.7
A06	51	33	L(No)	Above hand	Mioelectric/5	Rarely	Daily	2.8	33.1
A07	51	36	L(Yes)	Through elbow	Mechanic/5	Daily	Daily	15.1	−17.4
A08	51	29	R(Yes)	Below elbow	No/0	Never	Never	69.6	−7.6
A09	25	25 (cong)	R(n/a)	Above hand	Cosmetic/5	Never	Never	6.9	26.8

Frequency of use of residual arm was assessed using a questionnaire [0—never, 1—rarely, 2—occasionally, 3—daily (<4 h), 4—daily (4–8 h), 5—daily (>8 h)]. None of the congenital amputees had residual fingers. Amp., amputation; L, left; R, right; cong, congenital amputee (i.e., amilian; self-report); n/a, not applicable; comp, spatially compatibility; afford, affordance. Spatially compatibility effect size = incompatible - compatible; Affordance effect size = non-graspable - graspable.

to ensure that the participants processed the image content, as studies have shown only an in-depth processing of the object is likely to induce an affordance effect (Symes et al., 2005; Pellicano et al., 2010). Stimulus-response mapping (left for metal, right for non-metal, and vice versa) was counterbalanced between subjects.

The responses were given either through button presses on a standard keyboard with the left or right index finger ("A" key or "num 6" key, respectively), or by lifting the arm to perform a reach-like movement toward the screen with the left or right arm, measured with EMG over the middle deltoid muscle. Participants were asked to raise the arm to shoulder height, such that the left/right hand (if available) was touching the left/right side of the screen (respectively) where the object images had been projected. To ensure that the participants were familiar with all the stimuli and were able to respond correctly, each session began with a slow presentation of the objects containing metal in the center of the screen, followed by the objects not containing metal. This was followed by a short training period (using two buttons), in which each object image was presented for 700 ms on either the left or the right side of the screen, and participants had to respond as quickly as they could. Following each trial in the training session, feedback was provided for both the accuracy and speed of the response.

After the training, participants performed two sessions where feedback was not provided. Each stimulus appeared 4 times (twice on the right and twice on the left side), with a total of 96 trials in each session. The amputee participants performed shorter sessions, with a total of 48 trials each.

EMG RECORDING AND PREPROCESSING

Adhesive disposable surface electrodes were placed over the right and left middle deltoid muscles in a belly-to-tendon fashion, with a reference electrode placed on the collar bone. EMG recording was triggered by Presentation software at the onset of each image presentation, using a sample rate of 2000 Hz. The signal was digitized using LabVIEW® and data were analyzed using custom scripts (available from the authors) in Matlab (MathWorks, Natick, MA). Offline, the data were segmented into 2000 ms epochs, baseline corrected, bandpass filtered with a dual-pass 4th order Butterworth filter (25–250 Hz), rectified, then low-pass filtered (<250 Hz). The baseline was defined as the first 100 ms of each trial (a voluntary EMG response typically has more than 120 ms latency; see Pruszynski et al., 2008). Single-sample "spike" artifacts were removed by interpolation. EMG data were analyzed by extracting a number of parameters: (1) the onset of voluntary EMG activity ("EMG onset"), defined as the first time-point after the baseline period (100 ms) for which the following 10 ms had a mean EMG activity greater than 3.09 standard deviations above the baseline mean EMG activity (i.e., where $p < 0.001$) (see Hodges and Bui, 1996). These parameters were chosen primarily for their robustness in discarding small spikes that were not followed by a full EMG response. (2) The latency of the maximum amplitude of the response ("EMG max"). This measure was chosen as a landmark in the reaching movement, due to its high correlation with button press reaction times, while measured from the same muscle (**Figure S1**). This measurement represents a later component of the movement.

EMG ANALYSIS

In order to determine which of the two arms (left or right) was the responding arm, the maximum amplitude of each of the two EMG channels (left and right arms) was logged. The maximum amplitude values from each arm were normalized by dividing each value by the mean maximum amplitude across all trials with that arm. In each trial, the two normalized maximum amplitudes were compared. The arm more active in the trial (i.e., showing the highest normalized maximum amplitude) was defined as the responding arm, and its onset and maximum latencies were taken as reaction times (RTs). The onset of the EMG responses was expected to capture effects at the very early stages of the movement, reflecting sensory (and more automated) processing, with respect to later, more cognitive influences on motor execution (Lacouture and Cousineau, 2008). The maximum of the EMG response, was expected to reflect a later stage of motor response, corresponding to a button press (see **Figure S1**).

FIGURE 1 | Stimuli and experimental design. (A) The object images used in the experiment. Each graspable object had a non-graspable counterpart, with similar asymmetrical features. Images were projected on a large screen, such that each image was presented near the left or right shoulder of the participants. **(B)** Experimental design. A 2 × 2 factorial design was used, with factors: graspability (graspable, non-graspable), and spatial compatibility (compatible, incompatible). The resulting four trial types are demonstrated, using one pair of objects. The hand illustrates the limb that will result in a correct response, and the cross illustrates the fixation point (in this example, subjects were asked to respond to metal objects with their right arm). Stimulus-response mapping was counterbalanced between subjects.

In order to display the mean EMG signal in each of the experimental factors (spatial compatibility and affordance, **Figures 2A,B**), the following additional steps were taken: Data were normalized to the mean of the maximum EMG of each of the participant's muscles to reduce between-participant and between-arm variability, and a further 50 Hz low-pass filter was used (note that this was done for visualization purposes only). Data from correct trials were sorted into 4 conditions for each of the two experimental factors: spatial compatibility (compatible vs. incompatible) or graspability (graspable vs. non-graspable) and for each arm (responding vs. non-responding). The mean EMG signal (across trials per condition then across participants) was plotted for each condition.

To plot the spatial compatibility and affordance effect sizes, the differences between the means of factor levels (compatible vs. incompatible and graspable vs. non-graspable) were calculated for each participant separately for the responding arm and the non-responding arms. Then the mean of all participants was plotted and statistical tests were performed to find time points significantly different from baseline ($p < 0.01$, two tailed) in each curve.

"TWITCH" ANALYSIS

In order to identify an early and automatic component of the motor responses, twitches were defined as follows: a significant elevation in EMG signal above baseline in the incorrect hand (i.e., the hand that would yield an incorrect response), which occurred prior to the correct hand response onset. The same onset criteria as "EMG onset" were used to determine EMG "twitches." The percentage of twitches in each condition was calculated as the percentage of trials in which twitches were detected, out of the total number of trials in each condition (including error trials). Twitch data of one participant were lost due to a technical error.

STATISTICAL ANALYSIS OF RESPONSE LATENCIES AND REACTION TIMES

The EMG parameters and button press reaction times (RTs) were analyzed using Excel and Matlab. Each trial was assigned to one of four conditions, based on two factors: spatial compatibility (between the stimulus position and the responding hand, compatible vs. incompatible) and affordance (graspable vs. non-graspable, see **Figure 1B**). RTs on incorrect trials were discarded, as well as RTs longer than 1500 ms. RTs of each condition were averaged within each subject, and a Two-Way repeated measures ANOVA was performed using Matlab (spatial compatibility × affordance). Due to the small sample sizes used in this study, significant results of each test were further validated using the Wilcoxon rank sign test, which yielded similar results to the ANOVA main effects. Wilcoxon tests were also performed to test for compatibility and affordance effects in the error rates (calculated as percentage of incorrect responses out of the total number of trials in each condition). Effect sizes were calculated both by differences between the means (spatially incompatible-compatible and non-graspable-graspable), and as Cohen's d using online software (http://www.cognitiveflexibility.org/effectsize/).

For the amputee group, an additional factor of the amputated vs. intact arm was tested against the spatial compatibility and manipulability effects, resulting in a 3-way repeated measures ANOVA (spatial compatibility × affordance × arm). To account for variance in performance, resulting from amputation-related visuospatial perceptual biases, we used individuals' point of subjective equality (PSE; Makin et al., 2010) as a covariate in a further

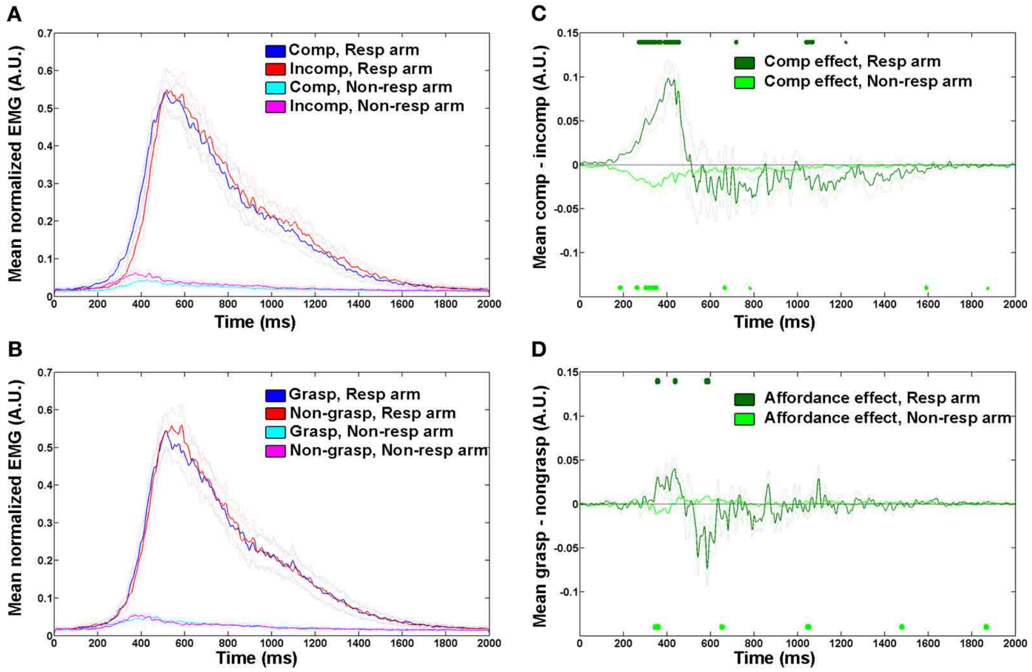

FIGURE 2 | Mean EMG traces showing spatial compatibility and affordance effects. (A,B) Mean normalized EMG trace across all trials and participants in each condition in responding and non-responding arm for **(A)** spatial compatibility effect; **(B)** affordance effect. Dotted lines denote between-participant variability (SEMs). Time zero on the x-axis represents the stimulus presentation onset. **(C,D)** effect sizes in the responding- and non-responding arms for **(C)** spatial compatibility effect, calculated by (compatible—incompatible) mean response, **(D)** affordance effect, calculated by (graspable—non-graspable) mean response. Dotted lines denote between participants variability (SEMs). Circles on the top and bottom of plot indicate time points significantly different from baseline ($p < 0.01$, two-tailed). Comp, spatially compatible; incomp, spatially incompatible; resp, responding; grasp, graspable.

3-way ANCOVA. The PSE measure captures lateral asymmetry in visuospatial representation of near space, as measured in a "landmark" task (for further details see Makin et al., 2010).

OBJECT FAMILIARITY ANALYSIS

In a *post-hoc* analysis, an observer, unaware of the study purposes, was asked to name each of the objects used in the study. Each object was then checked for prevalence in a large word and phrases corpus (google books Ngram Viewer, Michel et al., 2011). For each word the percentage of its appearance out of all the phrases of the same length in the corpus was calculated (in the Hebrew database between the years 2000 and 2008). Then the mean prevalence in each object group (graspable and non-graspable) was calculated and a two-tailed t-test was performed.

RESULTS

EMG OF REACHING-LIKE MOVEMENTS EXPERIMENT

We first explored the spatial compatibility and affordance effects by plotting the mean EMG response of correct trials in the spatially compatible and incompatible conditions, for both the responding arm and the non-responding arm (**Figure 2A**). The response dynamics in this reach-like movement were of a quick elevation and a slower decay of the EMG signal, until it returned back to baseline at around 1800 ms from trial onset. In accordance with previous studies, we saw an earlier onset of the motor response for the compatible condition compared with the incompatible one. To better visualize the effect, we plotted the mean difference between spatially compatible and incompatible conditions in each time point of the trial. This allowed us to identify a clear increase in EMG signal in the spatially compatible condition in the responding arm around 250–450 ms from trial onset, deriving from an earlier rise in the signal (**Figure 2C**). A homologous effect was observed in the non-responding arm, where the incompatible condition had a higher amplitude and earlier onset. This could imply an arousal of the hand closest to the stimulus, even in the absence of a full motor response.

For the affordance effect we observed a smaller difference between graspable and non-graspable conditions (**Figure 2B**). The response to the graspable condition preceded that of the non-graspable condition at the very early stages of the response, at around 350 ms from trial onset (**Figure 2D**).

To quantify these observations and determine the relative contribution of affordance and spatial compatibility effects at early vs. later stages of the movement, we measured EMG onset and maximum amplitude latencies in each individual trial. When considering the onset of the voluntary EMG response (**Figure 3A**), we found significant spatial compatibility and affordance effects [$F_{(1,\,9)} = 11.46$, $p = 0.008$ and $F_{(1,\,9)} = 7.11$, $p = 0.026$, respectively] with large effect sizes (45 ± 13 ms, Cohen's $d = 1.6$ for spatial compatibility, and 9 ± 3 ms, Cohen's $d = 0.9$ for affordance), and no interaction [$F_{(1,\,9)} = 0.06$, $p = 0.815$]. These results suggest that both spatial compatibility and affordance effects are

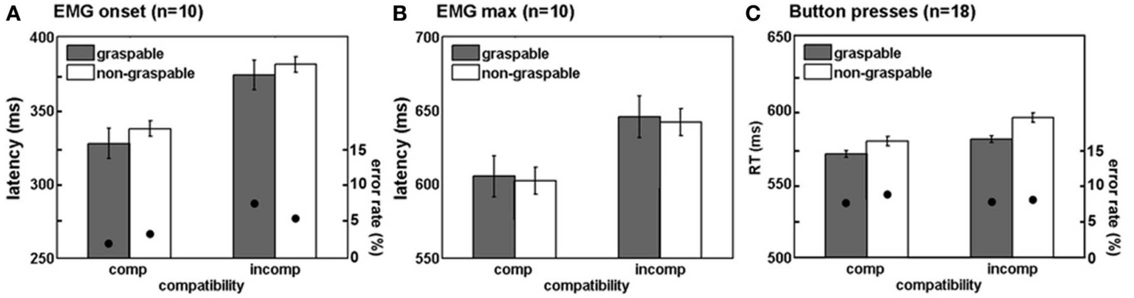

FIGURE 3 | Reaction time and EMG latency results show independent spatial compatibility and affordance effects. Mean reaction times or EMG latencies (bars, left scale) and error rates (black circles, right scale) for intact participants for the four trial types comprising the factorial analysis (see **Figure 1B**), during onset of electromyography (EMG) response **(A)**, maximum amplitude of EMG response **(B)**, and button press responses **(C)**. Comp, spatially compatible; incomp, spatially incompatible. Error bars indicate confidence interval for means, while taking into account the within-participant design (Cousineau, 2005; Morey, 2008).

present at the early component of the movement. In the later stage of response, when the EMG response is maximal (**Figure 3B**), the spatial compatibility effect was still evident [$F_{(1,\ 9)} = 5.32$, $p = 0.046$] albeit smaller (40 ± 17 ms, Cohen's $d = 0.8$). The affordance effect was gone [$F_{(1,\ 9)} = 0.41, p = 0.430$], and no significant interaction between spatial compatibility and affordance was found [$F_{(1,\ 9)} = 0.01, p = 0.974$].

This might imply that while the spatial compatibility effect has an extended time-window, a more transient influence of affordance restricts it to the earlier stages of the motor act. Alternatively, it might be possible that since the values of maximum EMG response are more variable, this measure is less sensitive to the small affordance effect. To address this potential confound, we calculated the coefficient of variation (CV) for each participant (SD/mean calculated for both onset and maximum latencies). This analysis revealed that the EMG max was less variable, compared with the EMG onset ($CV_{\text{onset}} = 0.31 \pm 0.006$; $CV_{\max} = 0.22 \pm 0.003$, $p = 0.001$ in a 2-tailed t-test). Moreover, the mean affordance effect, as displayed in **Figure 2D**, suggests that by the time the EMG response is maximal (at around 600 ms), the affordance effect is abolished (as reflected in higher EMG amplitude to the non-graspable conditions).

BUTTON PRESS RESPONSE EXPERIMENT

Next, we studied the spatial compatibility and affordance effects using the same set of stimuli but with a more conventional button press response. Using a larger group of 18 participants, we identified significant compatibility and affordance effects [$F_{(1,\ 17)} = 8.32$, $p = 0.01$ and $F_{(1,\ 17)} = 7.27$, $p = 0.015$, respectively; **Figure 3C**], again with no interaction [$F_{(1,\ 17)} = 1.25$, $p = 0.27$]. However, effect sizes were smaller (13 ± 4 ms, Cohen's $d = 0.7$ for spatial compatibility and 12 ± 4 ms, $d = 0.65$ for affordance) suggesting that the traditional button response approach is less sensitive in capturing the early stages of the response (as shown using EMG onset), and therefore requires a larger sample size to reveal both effects. When examining a subgroup of 12 participants that performed the button press experiment but not the EMG experiment prior to it, the effects were mostly retained [$F_{(1,\ 11)} = 4.16$, $p = 0.06$ for spatial compatibility effect, and $F_{(1,\ 11)} = 6.45$, $p = 0.027$ for affordance effect].

"TWITCH" RESULTS

To study motor responses to the visual stimulus that are potentially involuntary, we assessed EMG activity prior to the correct response in the incorrect hand ("twitches"). During incompatible trials, participants are required to suppress an early response with the arm that is spatially compatible with the stimulus, in order to respond correctly. This process might account to some extent for the delayed responses in spatially incompatible (compared to compatible) trials. Moreover, we were interested to see whether graspable object images would induce more twitches than non-graspable images, due to their motor arousal effect. In the present study, participants produced more twitches in spatially incompatible trials, as compared to compatible trials. In other words, the non-responding arm was more active when the objects were presented next to it, resulting in a trend toward a significant spatial compatibility effect [$F_{(1,\ 8)} = 3.82$, $p = 0.08$; **Figure 4**]. However, similar trends were not found for the affordance effect [$F_{(1,\ 8)} = 0.06, p = 0.8$], or for an interaction with the affordance effect [$F_{(1,\ 8)} = 0.11, p = 0.74$].

EMG OF REACHING-LIKE MOVEMENTS IN AMPUTEES

We tested our experimental paradigm on nine upper limb amputees using EMG of the deltoid muscles while they were performing reaching responses with their intact and residual arms. Since the effect size was greatest for EMG onset in the intact participants dataset, for the amputee group we focused our analysis on EMG onset latencies. No differences in onset latencies were found between movements executed with the intact arm and the residual arm ($p = 0.77$), and no interaction was found between the responding arm (intact vs. residual) and each of the other effects [$F_{(1,\ 7)} = 0.8$, $p = 0.39$ and $F_{(1,\ 7)} = 1.35$, $p = 0.27$, for spatial compatibility and affordance, respectively]. We therefore plotted the normalized mean EMG response, averaged across both arms, in a similar manner to the intact participants (**Figure 5**). The response dynamics were generally similar to those observed in intact participants (although relatively

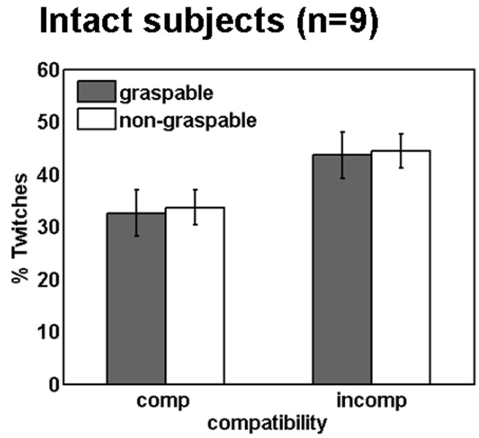

FIGURE 4 | Spatial compatibility effects during movement preparation in intact participants. Mean percentage of twitches (i.e., EMG activity in the hand irrelevant for response, see methods) in intact subjects. Annotations are as in **Figure 3**.

delayed), with a rapid rise of EMG signal and a slower decay toward baseline (**Figures 5A,B**). When considering the effect of spatial compatibility, the effect was restricted to the early stages of the movement (around 400 ms; **Figure 5C**), with the effect reversing as the amplitude for the incompatible condition reached its maximum (**Figures 5A,C**). In contrast, the affordance effect was completely absent in the amputee's data (**Figures 5B,D**). When applying a Three-Way ANOVA to the onset latencies we found a trend toward a spatial compatibility effect [$F_{(1,\,7)} = 3.6$, $p = 0.09$, 21 ± 4 ms, Cohen's $d = 0.72$], no affordance effect [$F_{(1,\,7)} = 0.89$, $p = 0.37$, -10 ± 4 ms, Cohen's $d = 0.37$] and no interaction [$F_{(1,\,7)} = 0.78$, $p = 0.39$; **Figure 6**]. When applying a 3-way ANCOVA, taking into account the spatial biases of each amputee participant (using individual PSE values as a covariate, see introduction and methods), we found a significant spatial compatibility effect [$F_{(1,\,7)} = 9.6$, $p = 0.017$], as well as a significant interaction between the spatial compatibility effect and the spatial PSE [$F_{(1,\,7)} = 10.1$, $p = 0.016$]. No other significant main effects or interactions were found ($p > 0.18$).

SPEED-ACCURACY TRADE-OFFS

In order to account for potential confounds resulting from speed-accuracy trade-offs, effects of spatial compatibility and affordance were also tested on the error rates in each of the experiments. None of the results were significant ($p > 0.15$), with the exception of a trend toward a significant spatial compatibility effect in the intact participants EMG data ($p = 0.06$), showing more errors were performed in the spatially incompatible condition.

ACCOUNTING FOR DIFFERENCES BETWEEN IMAGES

It could be argued that the affordance effect we found in the intact group was due to other parameters differentiating the object groups (like familiarity). To account for this potential confound we identified the frequency of appearance of the name of each object in a large word and phrases corpus (Michel et al., 2011). We found the mean frequency of appearance in the corpus was $4e^{-4} \pm 1e^{-4}$ for graspable and $9e^{-4} \pm 4e^{-4}$ for non-graspable objects, with no significant difference between the object groups ($p = 0.22$).

DISCUSSION

Using an ecological setup, with naturalistic images and whole arm reaching-like responses, we present new and converging evidence for the existence of an affordance effect independently of spatial compatibility. We found that in intact participants, responses to graspable objects were faster than to non-graspable objects, independently of spatial compatibility. These results were replicated both with button press responses, and when measuring the onset of a reach-like movement using EMG. The prevalent account of affordances, based on speeded RTs for graspable objects oriented toward the responding hand, suggests lateralized facilitation of the hand toward which the central object's handle is oriented (Tucker and Ellis, 1998; Phillips and Ward, 2002; McBride et al., 2012). When considering responses for graspable objects only, we found that RTs were speeded for the spatially compatible hand. However, RTs for non-graspable objects showed similar compatibility effects, resulting in no significant interaction between object position (spatially compatible vs. incompatible) and object affordance (graspable vs. non-graspable). The fact that we found no interaction but two independent main effects suggests that graspable objects induce general arousal of the motor system, rather than evoking a specific potential motor action, based on the best motor plan afforded by the objects' position (as suggested in Gibson, 1979; Makris et al., 2011). Our results therefore support the view advocated by Cho and Proctor (2010) and Kostov and Janyan (2012) that the affordance effects, as shown for lateralized object positions (Tucker and Ellis, 1998; Phillips and Ward, 2002; McBride et al., 2012) may have been partly due to orientation of spatial attention toward the handle, leading to a classic spatial compatibility effect.

While we demonstrated the independent presence of the affordance and the spatial compatibility effects using the "classical" button press paradigm, both effects were more evident (as demonstrated by larger effect sizes) when responses were measured using a more ecological motor response (EMG recordings of reach-like movements). The EMG recordings also enabled us to monitor more closely the time course of each of the two effects. We found that the spatial compatibility effect was present from the earliest stages of movement preparation ("twitches"), through early stages of movement execution (EMG onset) and to the late stages of the response (EMG max). The affordance effect, on the other hand, was relatively short-lived, as it was restricted to the early stages of movement execution (EMG onset). A recent study by McBride et al. (2012) reported speeded responses (using EMG recording of distal hand muscles) in the hand corresponding to the object handle position, however this study did not account for non-graspable objects. Our results extend these findings by providing further evidence for the existence of an affordance effect as an early and transient component of motor control.

The use of EMG also made it possible for us to look at early motor activity in the non-responding hand. We found that more twitches were made on spatially incompatible trials (i.e., when the stimulus was presented near the non-responding hand), resulting in a trend toward a significant compatibility effect. This trend

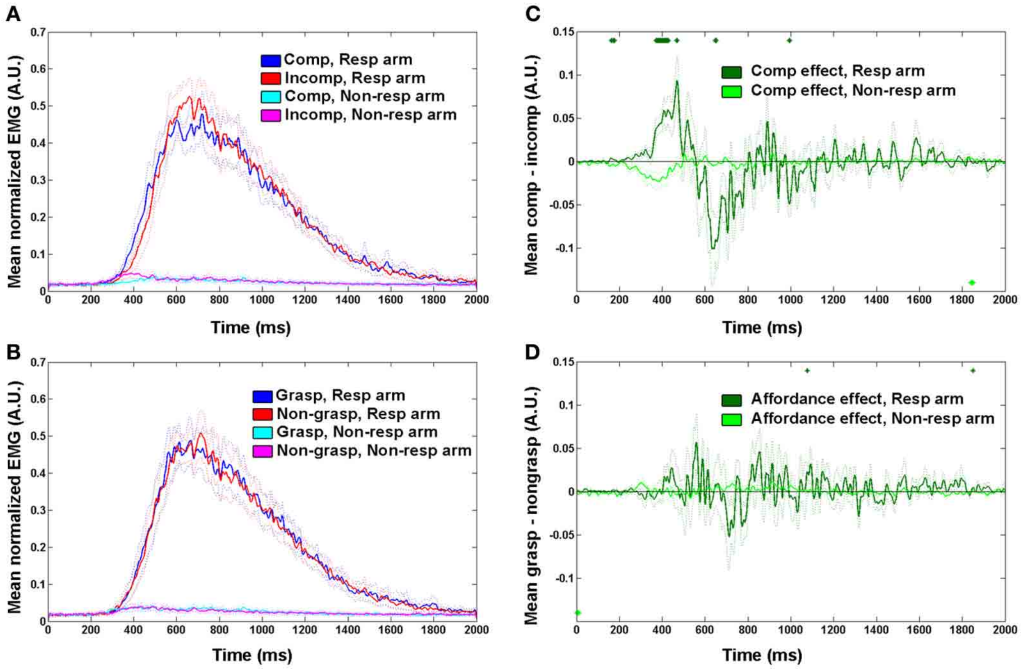

FIGURE 5 | Mean EMG traces for (A) spatial compatibility effect; (B) affordance effect. Effect sizes for **(C)** spatial compatibility effect; **(D)** affordance effect. Annotations are as in **Figure 2**.

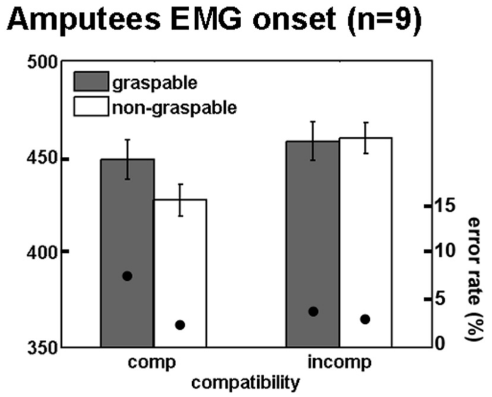

FIGURE 6 | Maintained spatial compatibility effect in unilateral upper limb amputees. Mean reaction times and error rates for amputees for the four trial types comprising the factorial analysis, during onset of EMG response. Annotations are as in **Figure 3**.

is in line with the "activation suppression hypothesis," which posits that in order to perform an incompatible response, it is necessary to first suppress compatible motor responses from the non-responding hand (Ridderinkhof, 2002). Similar results were observed by Burle et al. (2002), who measured EMG of distal muscles during a spatial compatibility task. The authors found that the prolonged RTs in incompatible trials corresponded to the existence of "twitches" in the wrong hand during the preliminary response stages of those trials. We found no evidence for early competition in response selection for graspable objects (compared with non-graspable objects). While null results should be interpreted with caution, this result might further support the notion that the affordance effect is not effector specific, because the graspability of the object did not provoke a competition between the two hands, but merely a speeding of response in the responding hand.

The spatial compatibility effect was also observed in the EMG responses of unilateral upper-limb amputees. Importantly, this effect was exposed only after accounting for the contribution of the visuospatial perceptual asymmetry that resulted from the amputation. This might imply that several independent processes may be influencing the amputees' performance, such that it is necessary to tease apart factors contributing to both maintained and altered visuospatial representations in order to interpret their behavior. A recent study showed that stimulus-response compatibility effects between two fingers of the intact hand are unaffected by amputation (Philip and Frey, 2013)—right finger responses were made more quickly to stimuli presented on the right side of the screen as compared to stimuli presented in the middle or the left of the screen, while left finger responses were quicker for stimuli presented on the left. This suggests that the spatial compatibility effects within the intact hand are maintained following amputation. Our results extend this notion, by demonstrating that bimanual response-selection mechanisms underlying spatial compatibility effect are still preserved to some extent, and do not exclusively depend on recent experience.

Research with special populations provides an exciting opportunity for teasing apart the affordance and spatial compatibility effects. For example, it has been shown that in healthy volunteers, but not in Parkinson's patients, a compatibility effect was enhanced by graspable stimuli (i.e., door handles;

Poliakoff et al., 2007) (However, note that in this study graspable objects had been shown to result in longer RTs, compared to non-graspable objects (bars), making any further interpretation of the relationship between compatibility and affordance tenuous). While we found clear evidence for a compatibility effect, we could not find any traces of an affordance effect in amputees, or an interaction between affordance and spatial compatibility or responding hand. These results therefore support the notion that the affordance effect we identified does not depend on a lateralized action plan, as considered before (Tucker and Ellis, 1998). Rather than being body-part specific, object affordance may depend on the indiscrete functioning of the motor system, however more research is needed to carefully assess the affordance effect on amputees.

The ecological design that we used in this study raises several methodological confounds that might be worth considering. First, EMG recording from proximal muscles might be considered more relevant for reaching than for grasping movements. However, while reaching and grasping movement components have specialized neural mechanisms (Cavina-Pratesi et al., 2010a,b), previous research points at a tight dependence and coordination between those two types of movements. Perturbation of only one of the components affects the dynamics of the other (Paulignan et al., 1991a,b; Jeannerod, 1999), and designated brain regions support their coordination in a reach-to-grasp movement (Cavina-Pratesi et al., 2010b). For this reason, we expect to identify changes in proximal muscles associated with graspable object features. Indeed, the dissociation between the two image categories we used as stimuli more critically depends on their potential for execution of a grasping movement, rather than their reachability (while a car in itself is typically non-graspable, it is nevertheless reachable). Accordingly, we identified comparable affordance effects using both proximal muscles (EMG recordings) and distal muscles (button responses).

A second potential confound arises from the use of naturalistic stimuli, which are more susceptible to confounds deriving from unexpected differences between object groups. To reduce this confound, we attempted to span a relatively large range of stimuli, with similar familiarity. But other parameters may influence the results. For example, non-graspable objects are typically larger in real life than graspable objects. Previous studies have found that large objects typically show faster responses than small objects (though non-significant, Tucker and Ellis, 2004; Vainio et al., 2006), thus this confound probably cannot account for the results we report. Similarly, a significant proportion of the non-graspable stimuli were natural, rather than man-made. But given the judgment participants were making (whether the object contains metal), responses should, if anything, have been faster for the naturalistic images (which usually do not contain metal). We therefore believe that the effect of affordance was likely based on the dissociation of the two groups into graspable and non-graspable objects, although more careful categorization of the stimuli is necessary.

To conclude, using EMG recordings of proximal muscles we demonstrate earlier motor responses to graspable objects, irrespective of whether the responding arm is most suitable to perform a reaching movement toward that object. Our results therefore prompt a revisit of the classical definition of the affordance effect as "operation of intentions to act on already existing motor representations of the possible actions in a visual scene" (Tucker and Ellis, 1998). Instead, our results suggest that graspable objects activate the motor system in a general, body-part independent fashion.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/Perception_Science/10.3389/fpsyg.2013.00591/abstract

Figure S1 | Relationship between EMG parameters of the first dorsal interosseous (FDI) muscle and index-finger button press reaction time (RT). Participants were required to perform a simple button press with their index finger in response to a visual cue. EMG was recorded from the FDI during task performance. The same EMG analysis was performed as described in the main text. The plots here show the relationship between RTs recorded using a button press and between EMG max **(A)** and onset **(B)** in one representative participant. Correlation coefficients (Pearson's r) were averaged for each individual across two hand positions, and then across 10 participants **(C)**. On average, both latencies of EMG maximum (max time) and onset showed strong correspondence with RT values ($p < 0.0001$). The area under the EMG envelop (area) also showed a significant relationship with RT values ($p < 0.05$), although to a much reduced extent. EMG amplitude (mV) at maximum latency (max amp) and mean amplitude during EMG baseline (mean baseline) didn't show any significant relationship with button press RT. Based on these findings, EMG maximum and onset latencies have been identified as the most relevant EMG parameters as proxies for RT. Error bars show s.e.m. Data was taken from Makin et al. (2009), Experiment 1.

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A brief review of the role of training in near-tool effects

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Research suggests that, like near-hand effects, visual targets appearing near the tip of a hand-held real or virtual tool are treated differently than other targets. This paper reviews neurological and behavioral evidence relevant to near-tool effects and describes how the effect varies with the functional properties of the tool and the knowledge of the participant. In particular, the paper proposes that motor knowledge plays a key role in the appearance of near-tool effects.

Keywords: peripersonal space, motor learning, motor control, multisensory integration, tools

One of the most surprising and interesting findings in research on near-hand effects is the possibility that they may also apply to the functional end of hand-held tools and virtual tools. Perhaps one of the reasons tool-users behave as if the tool is a part of their body is that the same neural mechanism responsible for signaling the visual and tactile border-zone between our bodies and surrounding space adapts to code the space surrounding tools. So when an experienced hockey player carries the puck up the ice on his stick, it is possible that his brain responds to visual and tactile information about the puck as if he were carrying it in his hands.

The space within reach, known as peripersonal space, is represented by visual-tactile bimodal neurons. Bimodal neurons, discovered in the monkey ventral premotor cortex (PMv), putamen, and the intraparietal sulcus, have overlapping visual and tactile receptive fields (vRFs and tRFs, respectively), typically on the face or hand (Rizzolatti et al., 1981a,b; Graziano and Gross, 1993; Graziano et al., 1994; Fogassi et al., 1996; Graziano, 1999; Graziano and Gandhi, 2000). Some also integrate auditory information (Graziano, 1999; Schlack et al., 2005). These neurons receive proprioceptive information (Rizzolatti et al., 1981a,b; Graziano et al., 1994; Graziano, 1999) and their vRFs remain anchored to the hand when it moves to a new location (Graziano et al., 1994; Graziano, 1999). Space near the hands (and face) is represented more densely than space far from the hands and face (Graziano and Cooke, 2006), and bimodal-cell firing rates gradually decay as the distance between the stimulus and the edge of the tactile RF increases (Graziano et al., 1994; Graziano, 1999). Interestingly, the vRFs of these neurons surround and extend beyond the tRF such that visual stimuli appearing near but not touching the skin (within the vRF alone) can also recruit these neurons. In short, visual information presented near the hands may recruit bimodal neurons, whereas visual information presented away from the hands may not. This recruitment has been cited as a possible mechanism underlying the special properties of peripersonal space and may play an important role in the representation of our body schema (Cardinali et al., 2009a).

Research suggests that when a monkey uses a hand-held tool, the size of the bimodal-cell vRF adapts to encompass the tool and that tool-use training plays a key role in this adaptation. Iriki et al. (1996) recorded from visual-tactile bimodal cells in the anterior bank of the intraparietal sulcus (a-IPS) both before and after monkeys practiced using a light, plastic rake to retrieve a food pellet. They recorded activity in both "distal" cells, whose tRF was on the skin of the hand, and "proximal" cells, whose tRF was on the skin of the shoulder. Before training, the vRF of distal cells surrounded the skin and space near the hands only, but after 5 min of rake use, the same neurons responded to stimuli presented near the tool tip. The vRF of proximal cells showed a similar pattern of adaptation: before training, the vRFs encompassed reach space of the arm and hand, but after training, the same vRFs grew to encompass the area reachable with the tool-in-hand. Importantly, these changes were induced only after active tool use, and not after the monkeys held the tool passively for the same duration. The importance of training was underscored by Obayashi et al. (2000), who reported that hand-movement training caused previously unimodal somatosensory neurons in the post-central gyrus of the macaque parietal cortex (Iwamura et al., 1993) to become sensitive to near-hand visual stimuli (i.e., unimodal tactile neurons became bimodal neurons after training). In short, active use of the hand (Obayashi et al., 2000) or a hand-held tool (Iriki et al., 1996; Maravita and Iriki, 2004) may change how the CNS represents the space surrounding the hand or tool.

NEAR-TOOL EFFECTS IN HUMANS ARE DEPENDENT ON ACTIVITY

As documented in this issue, there has been a great deal of research exploring the possibility that humans also possess neural systems that respond when visual stimuli are presented near the hand (Makin et al., 2007; Brozzoli et al., 2011; Gentile et al., 2011) and, in parallel, whether presenting a visual target near a tool will also influence the speed, accuracy, and variability of perception. One indicator of near-tool effects on perception in humans is the increased efficiency with which targets presented near the tool are processed (Maravita et al., 2001; Farnè et al., 2005a,b, 2007; Holmes et al., 2007a, 2008; Kao and Goodale, 2009; Short and Ward, 2009; Reed et al., 2010; Brown et al., 2011; Gozli and Brown, 2011; but see Holmes et al., 2007b). Another set of studies has shown that the features of visual processing that distinguish peripersonal (near) from extrapersonal (far) space are reduced or eliminated when patients and/or healthy participants use a tool that extends reach (Berti and Frassinetti, 2000; Pegna et al., 2001; Witt et al., 2005; Longo and Lourenco, 2006; Gamberini et al., 2008; Osiurak et al., 2012; Seraglia et al., 2012; Witt, 2011; but see de Grave et al., 2011).

The importance of active tool use (vs. passive holding) has been demonstrated in a series of studies study conducted by Farnè and his colleagues (Farnè and Làdavas, 2000; Farnè et al., 2005a,b, 2007) on visual tactile extinction. This cross-modal version of tactile extinction is observed in some patients with unilateral lesions (typically involving the parietal cortex). Even though a patient might be able to feel a tactile stimulus when it is presented by itself on the hand contralateral to the lesion, he or she will often fail to report that same stimulus when a visual stimulus is presented simultaneously near the ipsilesional hand; i.e., detection of the tactile stimulus is extinguished. In a case study of visual-tactile extinction, Farnè et al. (2005a) showed that extinction of a tactile stimulus presented on the contralesional hand also occurred when a visual stimulus was presented near the tip of a tool held in the ipsilesional hand after the patient had used the tool to rake in objects for 5 min, but not after the patient spent that time passively holding the tool. In a follow-up study, Farnè et al. (2005b) demonstrated that the strength of cross-modal extinction by the presentation of visual stimuli at the tip of the tool depended on the length of the tool used during training. Patients who trained with a 60-cm tool showed greater cross-modal extinction when holding a 60-cm tool than a 30-cm tool, and patients who trained with a 30-cm tool showed greater cross-modal extinction when holding the 30-cm tool. Finally, patients who held a hybrid tool in their ipsilesional hand that was 60-cm in length, but whose functional rake component was placed 30 cm from the hand, showed greater cross-modal extinction of the tactile stimulus on the contralesional hand when the visual stimulus was placed at 30 cm than at 60 cm. These results indicate that the functional length of the tool is more important than the physical length, and suggest that active training allows the user to learn about the capabilities of the tool from multiple sensory modalities.

Findings by Kao and Goodale (2009) also showed that near-tool effects are dependent on training and specific to the tool used during training. In their study, healthy participants trained with either a fake hand or a small rake. After training, fake-hand trainees showed enhanced detection for targets presented on the fake hand but not the rake, and rake-trainees showed enhanced detection for targets presented on the rake but not the fake hand. Enhanced target detection was documented only when the target was presented on the surface of the tool viewed during training. Reed et al. (2010) also found enhanced detection of targets presented near the tip of a rake that had been used to manipulate sand in a Zen garden. Reed et al. found that detection benefits were restricted to one side of the tool, but in this study, benefits were restricted to the functional side of the tool (tine-side). Together with the study by Farnè et al. (2005b), these studies suggest that near-tool effects do not always generalize to the entire tool, and that knowledge of the tool's recent function plays a key role in the appearance of near-tool effects.

Although many studies have focused on visual adaptation, tool-use-dependent changes in the representation of space around the tool have also been documented in the auditory modality. Serino et al. (2007) found that when sighted participants were tested immediately after taking a cane in-hand, they responded more quickly to sounds presented near the hand than near the cane tip. After one day of cane use, this difference disappeared, indicating tool-use-related spatial adaptation. Experienced blind cane users, by contrast, did not need additional training to exhibit spatial adaptation to the tool. These results suggest that tool-related spatial adaptation is applicable to a broad range of sensory modalities and they highlight the importance of tool-use experience.

NEAR-TOOL EFFECTS DEPEND ON MOTOR CONTROL KNOWLEDGE

The observation that near-tool effects depend on some training suggests that there is a process of learning or recall of tool-related knowledge that needs to be invoked to induce spatial adaptation near the tool. One possibility is that this knowledge is motor in nature. Arbib et al. (2009) argued that tool representation must include both a mapping of tool reach to spatial locations so that peripersonal space can adapt to accommodate reach, and a mapping of tool function to hand movements so that the function of the tool can be linked to the hand movements that are required to effect that function (see also Frey, 2007). Both Làdavas and Serino (2008) and Makin et al. (2012) note that neural systems responsible for the sensory representation of the body overlap substantially with regions involved in sensorimotor control and emphasize the distinct visuomotor processing advantages that these links may provide.

The acquisition of motor knowledge involves establishing a reliable predictive relationship between the planned motor command and the visual, proprioceptive, and dynamic tactile sensory consequences resulting from its execution (Wolpert, 1997; Wolpert and Kawato, 1998; Flanagan and Beltzner, 2000; Flanagan et al., 2003). This acquired model of the limb (an internal model) generates motor commands—the directive for muscle activations—from planned movement trajectories. A second, forward model of the limb system predicts the resultant sensory outcomes from the motor command. These models must account for many factors, including physical factors like the mass and lengths of limb segments, gravity, and both directly- and indirectly-generated (interaction) torques about the joints (Sainburg et al., 1995, 1999; Wolpert and Kawato, 1998; Gribble and Ostry, 1999). Tool motor learning involves acquiring the ability to predict the sensory information that will result from the combination of limb and tool movement. When tools are added to the limb or hand, both the forward and inverse model must adapt to account for the additional mass and torque applied to the limb system (Sainburg et al., 1999; Bagesteiro and Sainburg, 2003; Wang and Sainburg, 2004). If participants have worked with the tool before, this adaptation may be expedited as they may access stored information about the tool's inertial profile (Haruno et al., 2001).

In short, motor knowledge may play a role in near-tool effects because it allows the user to make predictions about the spatial location of the working end of the tool as it is moved, linking limb, hand, and tool posture (signaled by the somatosensory system) to locations in space beyond the body (usually signaled by the visual system). Put differently, we may need to be able to control and reliably predict the tool's actions before changes in how space around the tool is represented can be implemented (e.g., adaptation of the vRF of visual-tactile bimodal neurons). Although not explicitly linked to motor knowledge *per se*, a promising computational model of the effects of tool use on the representation of peripersonal space relies on a predictive mechanism that contributes to spatial adaptation in multisensory cells (Magosso et al., 2010).

This view is supported by work showing that near-tool effects can be directly linked to action preparation (Collins et al., 2008; Brozzoli et al., 2010) and by studies indicating that active tool training changes participants' implicit representation of the extent and shape of their own limb (Cardinali et al., 2009a,b, 2012; Sposito et al., 2012; Canzonieri et al., 2013). Berti and Frassinetti (2000) showed that near-space hemispatial neglect expanded to far space when neglect patient PP held a stick-pointer but not when she held a laser-pointer in which the sensation of the inertial forces and changes in the location of the laser light are uncoupled. A similar distinction has been demonstrated in healthy participants (Gamberini et al., 2008; Witt, 2011; but see Davoli et al., 2011). This latter result suggests that there may be a special role for objects whose reach (length) can be both seen and felt via tactile and proprioceptive cues signaling their inertia (Carello et al., 1998; Carello and Turvey, 2004).

A strong prediction of the motor knowledge hypothesis is that when participants are given a tool that is unfamiliar in terms of either inertial, spatial, or temporal dynamics, they will not show enhanced processing near that tool until its dynamics can be predicted in a way that the sensorimotor system finds useful. Brown et al. (2011) tested this hypothesis by presenting participants with a tool that had an unseen, off-center mass load, a feature that controlled for participants' tool-experience history. Testing revealed that participants who trained actively with the tool could control the tool better than people who received passive or no training, and that only participants in the active training group responded more quickly to detection targets when the tool tip was placed near rather than far from the display. The results support previous findings showing that active tool use plays a role in near-tool effects, and they suggest that active tool use is important for learning about the inertial dynamics of the tool.

The proposal that motor knowledge plays a key role in near-tool effects can also account for studies showing that near-tool effects can be detected with little or no training. For example, Holmes et al. (2007a) reported a reduction in interference associated with near-tool visual stimuli after only a very short duration of active tool use, and studies have found cross-modal interference for near-tool visual stimuli after simple real (Maravita et al., 2002) and virtual (Sengül et al., 2012) tool holding. Both children and adults adapted their estimates of reach distance to a pointing tool after a brief exposure (Caçola and Gabbard, 2012; Osiurak et al., 2012; Caçola et al., 2013), although older children (11+) adapted more effectively than younger children, and the efficiency of adaptation improves with age. It is possible that these studies found rapid adaptation of peripersonal space with tool use because, without exception, they used simple tools and/or toys (sticks, pointers, or toy rakes). Participants, even children, may have been able to (1) learn to control the tool very quickly, or (2) take advantage of their prior experience with tools to recall the necessary motor control information quickly (Imamizu et al., 2007; Serino et al., 2007; Massen and Prinz, 2009).

There has also been a great deal of interest in the role that multisensory systems and the motor system may be playing in our ability to treat virtual tools as if they are extensions of ourselves. In this domain, there has been emphasis on the idea that mechanisms involved in defining peripersonal space can extend to virtual tools (e.g., Bassolino et al., 2010; Sengül et al., 2012) and that motor agency may play a key role in this extension (Longo and Haggard, 2009; Short and Ward, 2009). Agency, in this case, is defined as the understanding that one's actions consistently cause the movement of a remotely displayed item or tool (e.g., mouse cursor). Agency has been manipulated by introducing temporal delays between movements made by the actor and movements of the virtual tool (Shimada et al., 2005; Longo and Haggard, 2009) or by presenting synchronous visual feedback only intermittently (Short and Ward, 2009; Nahab et al., 2011). These manipulations have shown that when one interferes with perceived agency for the observed limb, the visual facilitation associated with presenting stimuli near the virtual tool diminishes (Shimada et al., 2005; Longo and Haggard, 2009; Short and Ward, 2009; Nahab et al., 2011). Gozli and Brown (2011) investigated the role that motor control plays in near-virtual-tool effects by manipulating the spatial mapping between the movements of the user and the observed motion of the virtual tool. Participants were briefly exposed to three different spatial mappings between hand movements and motion of an on-screen mouse cursor. This mapping was either familiar (standard hand-cursor mapping), unfamiliar (reversed mapping), or absent (movements of mouse produced no cursor motion). Participants' ability to quickly detect the onset of cursor motion was then tested and revealed that participants exposed to the familiar-mapping condition responded more quickly than those exposed to the unfamiliar or no-mapping conditions. Given that participants in the unfamiliar mapping condition could still cause movements of the cursor in a temporally-consistent manner (they still had agency) but could not control them (their movements were slow and deliberate), Gozli and Brown argued that near-tool effects depend more on their knowledge of tool motor-spatial control than on tool agency.

Together, these results indicate that motor knowledge about the inertial and spatial dynamics of a tool play an important role in near-tool effects. When people are presented with standard tools, like wooden pointers, or with light easy-to-manipulate tools, like toy rakes, they are able to acquire or recall motor control information quickly. When the system is challenged by presenting participants with tools with novel inertial dynamics or with unusual spatial mappings, the dependence of near-tool effects on motor knowledge is more easily revealed. We may need to be able to control and reliably predict the tool's actions before changes in which the space around the tool is represented can be implemented in any sensory modality. This principle suggests that the future application of near-tool effects in occupational, educational, or rehabilitation settings will require close attention to the role of motor knowledge in tool use—and by extension its role in promoting the detection of stimuli around the "business-end" of tools.

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