

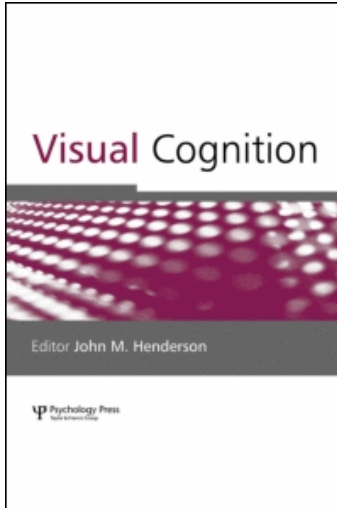
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Publisher Psychology Press

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## Visual Cognition

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title~content=t713683696>

### Grounding spatial language in the motor system: Reciprocal interactions between spatial semantics and orienting

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First published on: 17 August 2010

**To cite this Article** Gibson, Bradley S. and Davis, Gregory J.(2011) 'Grounding spatial language in the motor system: Reciprocal interactions between spatial semantics and orienting', *Visual Cognition*, 19: 1, 79 — 116, First published on: 17 August 2010 (iFirst)

**To link to this Article:** DOI: 10.1080/13506285.2010.495696

**URL:** <http://dx.doi.org/10.1080/13506285.2010.495696>

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## Grounding spatial language in the motor system: Reciprocal interactions between spatial semantics and orienting

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Shifts of attention that are directed by spatial words are thought to be mediated by a spatial frame of reference. Previous studies have documented a selection cost when visual attention is directed along the *left/right* axis relative to the *above/below* axis due to the greater ambiguity of the horizontal endpoints. The present study investigated whether the horizontal endpoints may be more fully disambiguated when “left/right” cues are first enacted by nondivisible, more discrete, modes of orienting such as directional motor responses. This issue was investigated using a repetition priming paradigm in which the effects of prior enactments were measured on the subsequent conceptual control of visual attention. The results of four experiments showed that grounding spatial language in the motor system can enhance the focus of visual attention by disambiguating the endpoints of the horizontal axis. In so doing, the present study extends previous research demonstrating that spatial concepts can influence the spatial distribution of attention by demonstrating that different modes of orienting can also influence the semantics of space. Implications for the premotor theory of attention and grounded theories of cognition are also discussed.

**Keywords:** Attentional control; Motor control; Spatial attention; Spatial semantics.

Speakers often use spatial language to orient the attention of listeners to relevant locations and objects in the environment (Clark, 1973; Coventry & Garrod, 2004); and spatial cueing studies confirm that projective word cues such as “above”, “below”, “left”, and “right” can reliably direct both voluntary and involuntary shifts of visual attention to cued locations (Gibson & Kingstone, 2006; Gibson, Scheutz, & Davis, 2009; Ho & Spence, 2006; Hommel, Pratt, Colzato, & Godijn, 2001; Logan, 1995; Mayer & Kosson, 2004; Vecera & Rizzo, 2004). What is less well known is how visual attention

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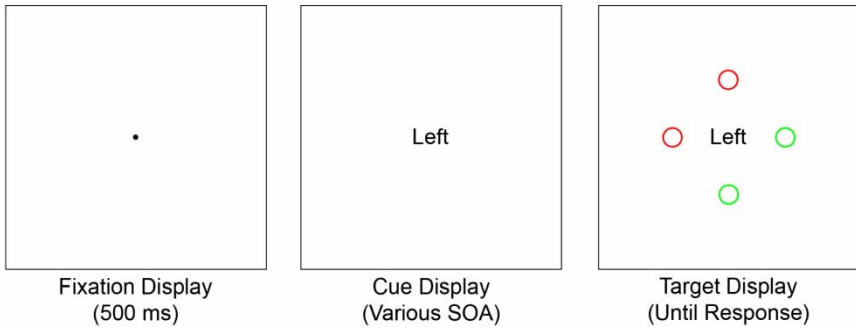
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<http://www.psypress.com/viscog> DOI: 10.1080/13506285.2010.495696

can be shifted from the reference object (the cue) to the located object (the target) in a spatially directed manner in these paradigms. As Logan (1995) pointed out, the mere indexing of the spatial locations of the cue and the target within a perceptual representation of the scene is not sufficient to mediate the spatially directed shifts of visual attention that occur in response to projective word cues, for such indexing does not adequately specify the spatial relation between the two objects. Rather, Logan argued that the spatial relation between these two objects must be specified with respect to a frame of reference (see also, for a fuller discussion of the role of reference frames in spatial language, Carlson, 2003; Kemmerer, 2006; Levinson, 2003).

Reference frames have been ubiquitous in the visual cognition literature, playing a central role not only in theories of spatial language, but also in theories of perceptual organization (Vecera, 2004), shape and object recognition (Humphreys, 1983; Marr, 1982), motor control (Soechting & Flanders, 1992), and spatial navigation (Seubert, Humphreys, Mueller, & Gramann, 2008). In general, a reference frame consists of a set of orthogonal axes that are defined by various parameters including: (1) The definition of an origin, which involves determining where the orthogonal axes will be centred; (2) the definition of orientation, which involves setting the horizontal and vertical orientation of the orthogonal axes; (3) the definition of direction, which involves labelling the end points of these axes; (4) the definition of scale, which involves specifying distance along these axes; and (5) the definition of regions of acceptability, which involves imposing a spatial template onto the axes that specify the acceptable and unacceptable regions of space associated with a particular spatial term (Logan & Sadler, 1996). Of critical importance is the notion that these parameters can be set relative to different sources of information leading to object-centred, environment-centred, or observer-centred frames of reference (cf. Levinson, 2003). Generally speaking, the present experiments will be concerned primarily with the observer-centred frame of reference. In these situations, the observer imposes his or her frame of reference upon the reference object.

Although an adequate understanding of spatially directed shifts of visual attention that occur in response to projective word cues appears to require a spatial frame of reference, relatively little is known about the functional consequences of such representations for attentional orienting and selection. Recently, Gibson et al. (2009) used the spatial cueing paradigm shown in Figure 1 to investigate the functional consequences of spatial frames of reference for the spatial distribution of visual attention (see also, Gibson & Kingstone, 2006; Logan, 1995). In this task, observers were required to discriminate the colour (red or green) of a circle that had been cued by one of four projective word cues on each trial (“above”, “below”, “left”, or “right”). The cues were 100% valid; in fact, the correct target could not be identified without the aid of the cue because the target display always



**Figure 1.** A typical display sequence from the spatial cueing paradigm used by Gibson et al. (2009). To view this figure in colour, please see the online issue of the Journal.

contained two red circles and two green circles. Logan (1995) argued that the use of 100% valid cues and ambiguous target displays was important for methodological reasons because it ensured that the spatial information provided by each of the word cues would be processed equally on each trial.

Current evidence obtained from this spatial cueing paradigm suggests that the computation of a spatial frame of reference has at least two characteristic effects on spatially directed shifts of visual attention: A *cued location effect* (Gibson & Kingstone, 2006; Logan, 2005) and an *opposite compatibility effect* (Gibson et al., 2009). The cued location effect reflects differences in the initiation of spatial orienting along the vertical and horizontal axes. In particular, attention can be oriented sooner to the above and below cued locations than to the left and right cued locations because the vertical axis can be accessed sooner than the horizontal axis.

The notion that the vertical axis may have primacy over the horizontal axis, and that it might be accessed sooner than the horizontal axis, has received support from a variety of different paradigms (Bryant, Tversky, & Franklin, 1992; Carlson & van Deman, 2008; Corballis, 1988; Franklin & Tversky, 1990). Reasons why the vertical axis may have primacy over the horizontal axis remain a matter of speculation, but possible reasons include its alignment with both the gravitational vertical and the canonical upright orientation of individuals, as well as the fact that the endpoints of the vertical axis tend to be asymmetric whereas the endpoints of the horizontal axis tend to be symmetric (Clark, 1973; Garnham, 1989; Levelt, 1984, 1996). Note, however, that Logan (1995) showed that directions specified along the vertical axis could be accessed sooner than directions specified along the horizontal axis even when the observer-centred frame of reference was dissociated from the environment-centred frame of reference, suggesting that this effect did not simply occur because *above* and *below* were aligned with the gravitational vertical.

In contrast, the opposite compatibility effect reflects differences in the spatial distribution of visual attention along the two axes. For instance, consider the colour of the circle that appears opposite the cued circle. On some trials, the colour of the cued circle and the opposite circle were compatible, but on other trials the colour of the cued circle and the opposite circle were incompatible. Gibson et al. (2009) showed that the incompatibility of the opposite circle caused greater interference when “left/right” cues were shown than when “above/below” cues were shown. In addition, Gibson et al. also included a probe RT task in which a target probe either appeared at the cued location, at the opposite location, at fixation, or at either pole of the orthogonal axis. These findings showed that visual attention was more divided across the horizontal axis in response to “left/right” cues than it was across the vertical axis in response to “above/below” cues. The opposite compatibility effect (and related probe RT findings) therefore reflect differences in the extent to which visual attention can be focused at different regions of space, with attention being less focused at locations specified along the horizontal axis (e.g., *left* and *right*) than at locations specified along the vertical axis (e.g., *above* and *below*).

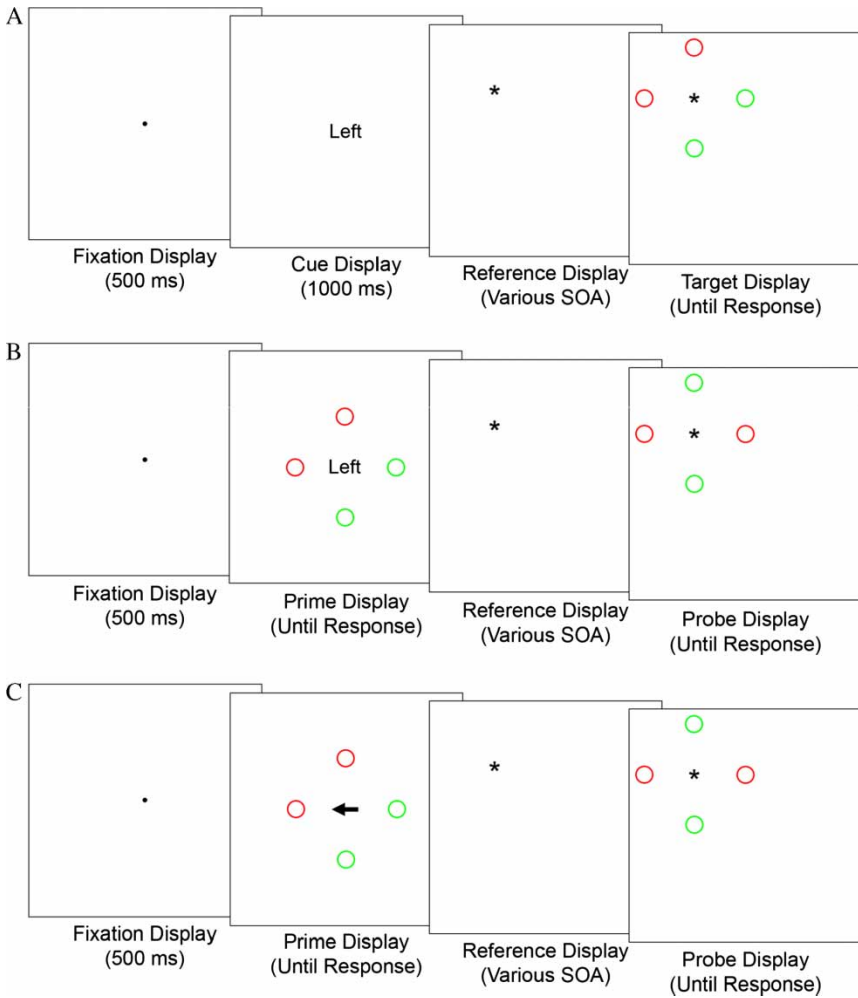
The opposite compatibility effect is thought to arise because directions such as *left* and *right* tend to be less stable than directions such as *above* and *below* as an individual moves about in the environment, or when two or more individuals communicate about space across opposing egocentric frames of reference (Schober, 1993, 1995). Consequently, the endpoints of the horizontal axis tend to be more ambiguous than the endpoints of the vertical axis. For instance, a chandelier may remain consistently above the table as an individual walks past the table and turns around, but a chair that was originally on the table’s left may now be on the table’s right following the same transformation. Gibson et al. (2009) argued that these differences in directional stability may have functional consequences for visual selection because these differences may translate into learned differences in cue validity over time, with “left/right” terms associated with lower spatial validity than “above/below” terms. Moreover, because experimental manipulations of cue validity are known to influence the focus of visual attention at a location (Johnson & Yantis, 1995; for reviews see, Pashler, 1998; van der Heijden, 1992), such learned differences may account for the wider distribution of attention that is characteristic of the opposite compatibility effect.

The conclusion that the distribution of visual attention can be influenced by the statistical structure of spatial semantics is important because it suggests that previously learned linguistic meanings can exert powerful control over visual attention. Indeed, the opposite compatibility effect reported by Gibson et al. (2009) was obtained under experimentally controlled conditions in which the spatial cue was always 100% valid, and the cued locations were consistently defined with respect to the observer.

Despite this consistency, the opposite compatibility effect persisted across the duration of the entire experiment and it was also observed across the entire distribution of response times (RTs). Thus, the opposite compatibility effect did not dissipate in magnitude as observers became more familiar with the experimental context; nor could this effect be attributed solely to the fastest or slowest RTs (which might reflect overly impulsive or spatially confused responding, respectively).

Note, however, that although the opposite compatibility effect provides evidence that preestablished semantic ambiguities associated with “left” and “right” can exert a persistent constraint on the spatial distribution of visual attention, the occurrence of this effect is also somewhat surprising given that semantic ambiguities are routinely encountered and resolved, if only momentarily, during the comprehension of everyday discourse (see Spivey, 2006, for a review; see also, Rodd, Davis, & Johnsrude, 2005). One reason the preestablished semantic ambiguities associated with “left” and “right” may not have been fully resolved in the spatial cueing experiments reported by Gibson et al. (2009) is because the distribution of visual attention does not demand disambiguation. In other words, spatially directed shifts of visual attention may tolerate directional ambiguity because the distribution of attention can itself be spatially ambiguous in the sense that it can be divided across multiple locations simultaneously. In contrast, other modes of orienting such as manual pointing are more discrete and cannot be divided in quite the same manner: The arm cannot be directed to multiple locations simultaneously. Consequently, spatially directed pointing responses may require stronger disambiguation of the endpoints of the horizontal axis than spatially directed shifts of visual attention before they are generated in response to “left/right” cues. Hence, the precise meaning of “left” and “right” in any given context may depend not only on the computation of axes and endpoints, but also on whether these terms are “grounded” in the attention system or in the motor system (Barsalou, 2008).

In the present study, the possibility that the dynamics of semantic disambiguation may interact with the mode of spatial orienting was investigated within the context of a repetition priming paradigm. In this paradigm, prime and probe displays were paired on each trial, and two orienting responses were performed in rapid succession (see Figure 2). The first orienting response (if required) was generated during the prime phase of the trial in response to spatial word cues (Experiments 1 to 3) or arrow cues (Experiment 4). Two different modes of orienting served as prime responses in the present study: Attentional orienting (Experiment 2) and manual pointing (Experiments 3 and 4). In addition, a third condition in which no orienting was required during the prime phase of the trial served as a baseline condition (Experiment 1). Regardless of the orienting response generated during the prime phase, the second orienting response always



**Figure 2.** Examples of the display sequences shown in the present experiments (see text for details). To view this figure in colour, please see the online issue of the Journal.

involved a shift of visual attention that was generated during the probe phase of the trial. By design, this second orienting response was always directed by the same spatial cue that appeared during the prime phase of the trial, though it was always initiated relative to a different reference object than the prime. In this way, we were able to evaluate whether the meaning of “left” and “right” was influenced by different modes of orienting; and then if so, whether these alterations in spatial semantics would be manifest in the control of subsequent shifts of visual attention.

Two primary questions were addressed in the present study. First, we investigated whether the endpoints of the horizontal axis remain at least partially ambiguous when spatial terms such as “left” and “right” are used to direct shifts of visual attention. This was accomplished by measuring the magnitude of the cued location and opposite compatibility effects observed during the probe phase when a prior spatially directed shift of visual attention was generated during the prime phase. On these trials, we hypothesized that the horizontal and vertical axes would be computed during the prime phase in response to “left/right” cues, but we also hypothesized that the endpoints of the horizontal axis would not be fully resolved in this condition. Consequently, we expected that these prior computations may facilitate access to the horizontal axis, but not disambiguation of the endpoints of this axis, during the probe orienting response. That is, we expected these prior computations to significantly reduce the magnitude of the cued location effect, but not the opposite compatibility effect, relative to the baseline. Note that the expected reduction in the magnitude of the cued location effect may be allowed because the two axes do not need to be computed *de novo* during the probe phase of the trial. As Logan (1995) stated, “the reference frame is a mechanism of attention that can be moved around space voluntarily just like spotlights and spatial indices” (p. 139). Thus, the axes might be reutilized during the probe phase of the trial, once they have been computed during the prime phase of the trial.

Second, we also investigated whether the endpoints of the horizontal axis would be more fully disambiguated when a manual pointing response was generated during the prime phase in response to “left/right” cues. If so, then we expected the prior computation of axes and endpoints during the prime phase in which a spatially directed pointing response was generated to significantly reduce the magnitude of the cued location and opposite compatibility effects observed during the probe phase in which a spatially directed shift of visual attention was generated. As such, the present study has the potential to shed light on how goal-directed motor actions can influence the control of attention (Eimer, Forster, van Velzen, & Prabhu, 2005; Gherri, van Velzen, & Eimer, 2009; Rizzolatti, Riggio, & Sheliga, 1994).

Note that this second prediction is founded on the assumption that there is a level of spatial representation at which both spatially directed movements of the arm and spatially directed movements of visual attention can share a common frame of reference (see also, Bekkering & Pratt, 2004). In their review of the neural representation of coordinate systems underlying various physical movements, Soechting and Flanders (1992) concluded over a decade ago that:

Representations of kinematics [i.e., movements] can be effector-independent, whereas codes of kinetics (or muscle activations) are not. Thus, the same

kinematic signal could be used to encode an orienting movement if it was effected by the eyes, the head, the body, or a combination of all three. The structure provided by kinematic codes in common coordinate systems can provide the ability for a system to process information from a variety of stimuli concurrently and to respond to one stimulus by a variety of movements. (p. 187)

Thus, it is likely that the meaning of spatial terms such as “above”, “below”, “left”, and “right” can be represented within a supramodal frame of reference that may be used to direct the movements of a variety of different orienting responses. Having said this, however, we also acknowledge that there may also be different domain-specific frames of reference that need to be computed across different modes of orienting. For instance, previous research has examined how individuals can point their arm to a visual target in three-dimensional space (see, for reviews, e.g., Flanders, Helms Tillery, & Soechting, 1992; Soechting & Flanders, 1992). This research has suggested that successful pointing to a visual target requires a transformation from a visually based, retina-centred frame of reference to a motorically based, shoulder-centred frame of reference. Moreover, arm movements must often take into consideration kinematic forces that influence directional responses, whereas covert shifts of visual attention do not (Soechting & Flanders, 1992). Thus, there may be other, more specific, levels of spatial representation at which spatially directed movements of the arm and spatially directed movements of visual attention do not share a common frame of reference. At the present point in time, we simply do not know which level (or levels) of reference frame processing are relevant for such cross-modal interactions. Fortunately, the present study will help fill this gap in knowledge by examining whether the computation of axes and endpoints underlying a spatially directed movement of the arm can influence the computation of axes and endpoints underlying a spatially directed movement of visual attention.

## EXPERIMENT 1

Experiment 1 was designed to serve as a baseline condition for subsequent experiments. In Experiment 1, a spatial word cue (“above”, “below”, “left”, or “right”) was presented at the central location for 1000 ms during the prime phase of the trial, but no orienting response was required (see Figure 2A). Following the presentation of the spatial word cue, a new reference object (an asterisk) appeared at one of four possible peripheral locations, which marked the beginning of the probe phase of the trial. Observers were instructed to shift their eyes to the asterisk and then orient their visual attention from the asterisk in accordance with the preceding spatial word

cue, which was always valid. The SOA between the asterisk and the target display was 0 ms, 500 ms, 1000 ms, or 1500 ms and varied randomly from trial to trial. Observers were instructed to discriminate the colour of the cued circle.

Previous evidence reported by Logan (1995, see Exp. 8), using a slightly different paradigm, has shown that the cued location effect can be observed under conditions in which the meaning of a spatial word cue is comprehended at one location and then used subsequently to direct visual attention from a reference object that appears at a different location. Based on this evidence, we expected that both the cued location and opposite compatibility effects would be observed during the probe phase of Experiment 1. Such findings would be important because they would show that both effects are not merely one-time costs associated with the comprehension of the spatial terms, but rather reflect costs that accrue when a spatial frame of reference is projected onto a reference object and then used to direct visual attention along the horizontal axis. More importantly for present purposes, such findings would enable us to investigate whether the reference frame processes that underlie various orienting responses generated during the prime phase in subsequent experiments can influence the cued location and opposite compatibility effects measured during the probe phase.

## Method

*Participants.* Thirty-two University of Notre Dame undergraduates participated to partially fulfil a course requirement. All participants reported normal or corrected-to-normal acuity and normal colour vision.

*Stimuli and apparatus.* A personal computer running DMDX software (Forster & Forster, 2003) with a 17-inch CRT monitor was used for stimulus presentation and data collection. Responses were collected using a custom-built response box with response time rounded to the nearest millisecond. A fixed viewing distance of 57 cm was enforced using a chinrest, and the experiment was conducted in a dimly lit room. Each trial consisted of four displays presented on a black background: A fixation display, a cue display, a reference display, and a target display. The fixation display consisted of a small white dot in the centre of the screen ( $0.38^\circ$  in diameter). The cue display contained one of the four spatial word cues (“above”, “below”, “left”, or “right”). Each cue was  $0.68^\circ$  tall and varied in length from  $1.18^\circ$  to  $1.94^\circ$ ; the words had white letters. The reference display contained a single asterisk ( $1^\circ$  in diameter) positioned in one of four quadrants on the screen: Upper left, upper right, lower left, and lower right. These four locations appeared  $4.37^\circ$  to the left or right of initial fixation, and  $4.37^\circ$  above or below initial fixation. The target display contained two red circles and two

green circles ( $1.26^\circ$  in diameter) that were located approximately  $4.37^\circ$  of visual angle from the location of the asterisk in each of the four cardinal locations.

*Procedure and design.* A typical display sequence in Experiment 1 is shown in Figure 2A. Each trial began with a fixation display for 500 ms followed by the cue display for 1000 ms which marked the beginning of the prime phase of the trial. The subsequent appearance of the reference display marked the beginning of the probe phase of the trial. Observers were instructed to keep their eyes fixed on the asterisk while shifting their visual attention to the spatial location that had been indicated by the spatial word cue (the cue was no longer present on the screen). The reference display was followed by the target display after a variable SOA of 0, 500, 1000, or 1500 ms; each of the four SOA conditions was presented randomly during the experimental trials. The target display remained on the screen until a response was made (or until 4000 ms elapsed). There were a total of six different target displays, which included all possible arrangements of the two red and two green circles; each cued location was paired with each of the six target displays equally often. The cues were 100% valid and always indicated which one of the four circles was the target. The cue referred to each one of the four cued locations equally often and, on any given trial, each cued location was equally likely to contain a red or green circle. In this way, observers could not determine (without guessing) how to respond without the aid of the cue. These contingencies provided reasonable assurance that observers would process each of the cues equally. Under these conditions, the colour of the opposite circle was incompatible with the colour of the cued circle on 67% of the trials; whereas the colour of the opposite circle was compatible with the colour of the cued circle on the remaining 33% of the trials.

Observers' task was to determine as quickly and as accurately as possible whether the target circle was red or green. Gibson and Kingstone (2005) investigated potential interactions between response orientation (response keys on the right or left of the response pad vs. on the top or bottom of the response pad) and cued location, but found no evidence of either facilitation or interference when, for example, observers had to orient to the left cued location and respond using the left or right key, respectively, relative to using the top or bottom key. Consequently, observers in the present studies always used their left hand to respond "red" and their right hand to respond "green". There were a total of 768 experimental trials that were preceded by 16 practice trials. A different random order was presented to each observer.

## Results and discussion

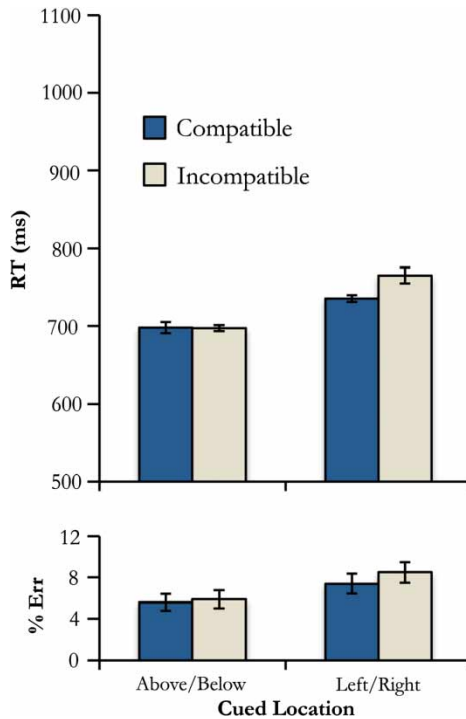
Mean correct RTs and error rates are shown in Table 1 as a function of SOA, cued location, and opposite compatibility. Both RTs and error rates were subjected to a three-way analysis of variance (ANOVA) with SOA (0 ms vs. 500 ms vs. 1000 ms vs. 1500 ms), cued location (above/below vs. left/right), and opposite compatibility (compatible vs. incompatible) as within-subjects variables. Note that the location of the reference object was not included as a factor in this or any subsequent analyses because Logan (1995) showed convincingly that this factor has no effect on performance in a paradigm that was similar to this one. Note also that initial tests revealed that the sphericity assumption was violated for effects involving SOA in both RT data and error rates. As such, a multivariate approach to analysing within-subjects factors was used in this, and all subsequent, experiments. In addition, omnibus significance was determined using  $\alpha = .05$ , partial eta-squared ( $\eta_p^2$ ) was reported as a measure of effect size, and Bonferroni corrections were used for planned post hoc comparisons in this, and all subsequent, experiments.

The cued location and opposite compatibility effects observed in the baseline condition are depicted in Figure 3. As expected, there was a significant cued location effect observed between the left/right and above/below cued location conditions. In addition, there was also a significant opposite compatibility effect observed in the left/right cued location condition, but not in the above/below cued location condition.

These conclusions were supported by ANOVA. With respect to mean correct RT, there was a significant main effect of SOA,  $F(3, 29) = 263.48$ ,  $p < .001$ ,  $\eta_p^2 = .96$ , indicating that RTs decreased as SOA increased. More importantly, there was also significant main effect of cued location,  $F(1, 31) = 27.55$ ,  $p < .001$ ,  $\eta_p^2 = .47$ , indicating that RTs were slower when “left/right” cues were shown than when “above/below” cues were shown. In addition, there was a significant Cued location  $\times$  Opposite compatibility interaction,  $F(1, 31) = 6.05$ ,  $p < .05$ ,  $\eta_p^2 = .16$ . Planned post hoc comparisons, with a Bonferroni-corrected critical  $p$ -value equal to .025, showed a significant effect

TABLE 1  
Mean correct RTs (ms) and error rates (%) listed as a function of SOA, cued location, and opposite compatibility for Experiment 1, with error rates in parentheses

SOA (ms)	Above/below		Left/right	
	Compatible	Incompatible	Compatible	Incompatible
0	902 (5.85)	900 (6.75)	961 (11.13)	999 (10.22)
500	672 (6.05)	663 (6.15)	692 (7.06)	738 (9.58)
1000	617 (6.12)	623 (5.96)	648 (5.07)	679 (7.24)
1500	601 (4.40)	603 (5.04)	641 (6.35)	643 (6.98)



**Figure 3.** Mean correct RTs (ms) and error rates (%) depicted as a function of cued location and opposite compatibility in Experiment 1. To view this figure in colour, please see the online issue of the Journal.

of opposite compatibility when “left/right” cues were shown,  $t(31) = 2.37$ ,  $p < .025$ , but not when “above/below” cues were shown,  $t(31) = 0.12$ ,  $p > .90$ . All other main effects and interactions were nonsignificant.

Note that the nonsignificant SOA  $\times$  Cued location interaction replicates RT findings observed in previous studies (Gibson & Kingstone, 2006; Gibson et al., 2009). Although it might be expected that slower access to the horizontal axis relative to the vertical axis should decrease as cue–target SOA increases, it is also reasonable to expect that differential access to the two axes will remain constant across SOA. For instance, Pylyshyn (1989, 1994, 2001) has argued that both the reference object (cue) and the located object (target) must be indexed before projective relations such as “above”, “below”, “left”, and “right” can be evaluated. However, further evidence will be required to distinguish this indexing hypothesis from alternative accounts; and, resolution of this issue is beyond the scope of the present article. For present purposes, recall that the potential for axis priming, which is expected in subsequent experiments, may still be observed across the prime

and probe trials, even if the indexing account is correct, because the two axes do not need to be computed *de novo* during the probe phase of the trial.

With respect to error rates, there was a significant main effect of SOA,  $F(3, 29) = 10.31$ ,  $p < .001$ ,  $\eta_p^2 = .52$ , indicating that observers committed fewer errors as SOA increased. There was also a significant main effect of cued location,  $F(1, 31) = 22.61$ ,  $p < .001$ ,  $\eta_p^2 = .42$ , indicating that observers committed more errors when “left/right” cues were shown than when “above/below” cues were shown. Additionally, there was a significant SOA  $\times$  Cued location interaction,  $F(3, 29) = 3.37$ ,  $p < .05$ ,  $\eta_p^2 = .26$ , indicating that the cued location effect decreased as SOA increased. All other effects were nonsignificant. These results provide no evidence of a speed–accuracy tradeoff that could compromise interpretation of the RT results.

## EXPERIMENT 2

Experiment 2 was designed to investigate whether the endpoints of the horizontal axis remain at least partially ambiguous when spatial terms such as “left” and “right” are used to direct shifts of visual attention. Accordingly, in Experiment 2, observers generated two spatially directed shifts of visual attention on each trial relative to two different reference objects (see Figure 2B). During the prime phase, a 100% valid spatial word cue (“above”, “below”, “left”, or “right”) was presented at the central location simultaneous with two red circles and two green circles; and, observers were instructed to shift their visual attention to the cued location and discriminate the colour of the cued circle. Consistent with previous studies (Gibson & Kingstone, 2006; Gibson et al., 2009; Logan, 1995), both the cued location and opposite compatibility effects were expected to be observed during the prime phase of the trial.

Following this response, the second reference object then appeared at one of the four possible peripheral locations, thus beginning the probe phase of the trial. As in Experiment 1, observers were instructed to shift their visual attention from the asterisk in accordance with the preceding spatial word cue. Of particular interest was whether the spatial computations presumed to underlie the cued location and opposite compatibility effects observed during the prime phase of the trial could influence the magnitude of these effects observed during the probe phase of the trial. In the present study, we hypothesized that the prior computation of the vertical and horizontal axes during the prime phase of trial should facilitate computation of these axes during the probe phase of the trial. Consequently, the cued location effect should be significantly reduced during the probe phase of the trial relative to the baseline condition of Experiment 1. More importantly, we also hypothesized that the endpoints of the horizontal axis should remain

ambiguous when “left/right” cues were shown during the prime phase of this experiment because the orientation of visual attention does not demand disambiguation. Consequently, any priming of endpoints that occurs during the probe phase should facilitate access to both endpoints. Hence, the opposite compatibility effect observed during the probe phase of this experiment should be approximately equal to that observed during the baseline condition of Experiment 1.

## Method

*Participants.* Thirty-two new University of Notre Dame undergraduates participated to partially fulfil a course requirement. All participants reported normal or corrected-to-normal acuity and normal colour vision.

*Stimuli and apparatus.* The stimuli and apparatus were very similar to those used in Experiment 1. The cue display used in Experiment 2 now included two red circles and two green circles in addition to the spatial word cue. The circles were  $1.26^\circ$  in diameter and each was located approximately  $4.37^\circ$  of visual angle from the centre of the display. All other displays were identical to Experiment 1.

*Procedure and design.* A typical display sequence in Experiment 2 is shown in Figure 2B. Each trial was divided into a prime phase and a probe phase. During the prime phase of the trial, the cue display appeared simultaneous with two red circles and two green circles, and remained visible until a response was made (or until 4000 ms elapsed). The cues were 100% valid and referred to each one of the four cued locations equally often. There were six different arrangements of the red and green circles, and each of the four cued locations was paired with each of the six circle arrangements equally often such that on any given trial, each cued location was equally likely to contain a red or green circle. Under these conditions, the colour of the opposite circle was incompatible with the colour of the cued circle on 67% of the trials; whereas the colour of the opposite circle was compatible with the colour of the cued circle on the remaining 33% of the trials. Observers' task was to determine as quickly and as accurately as possible whether the target circle was red or green. As in Experiment 1, observers always used their left hand to respond “red” and their right hand to respond “green”.

The probe phase of the trial began immediately following observers' response to the prime display and was identical to the probe phase used in Experiment 1. By design, observers always oriented their visual attention in the same direction across the prime and probe phases of the experiment (albeit relative to two spatially distinct reference objects); but, all other

experimental variables were randomly combined across these displays. For instance, the overall proportion of opposite-compatible (.33) and opposite-incompatible (.67) trials was the same across prime and probe phases. Because these displays were paired in a random fashion, the probability that an opposite-compatible display preceded another opposite-compatible display was  $.33 \times .33 = .11$ ; the probability that an opposite-compatible display preceded an opposite-incompatible display was  $.33 \times .67 = .22$ , as was the probability that an opposite-incompatible display preceded an opposite-compatible display; and the probability that an opposite-incompatible display preceded another opposite-incompatible display was  $.66 \times .66 = .44$ . Likewise, the probability that the same colour response was required across prime and probe displays was .50, as was the probability that a different colour response was required. As in Experiment 1, there were 768 experimental trials (each with two responses) that were preceded by 16 practice trials. A different random order was presented to each observer.

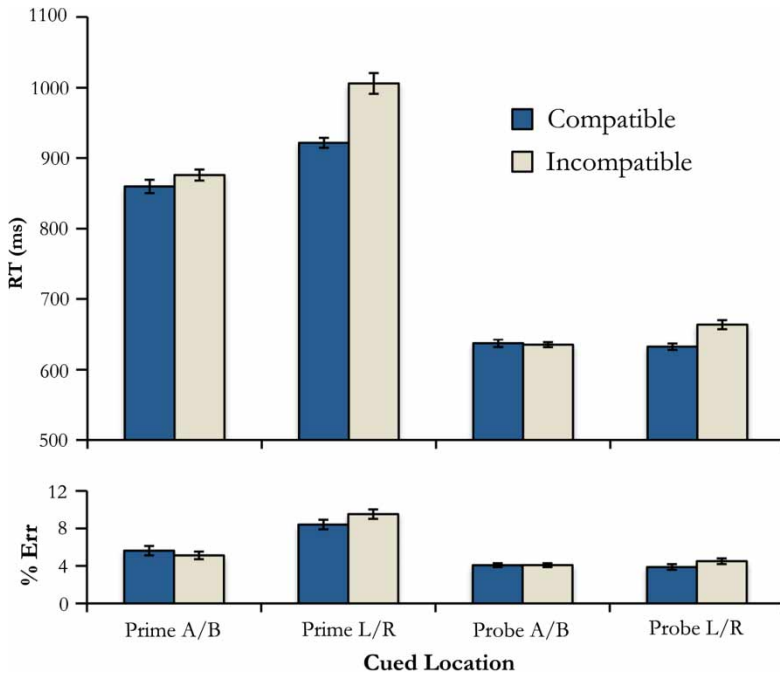
## Results and discussion

*Prime phase.* Mean correct RTs and error rates obtained during the prime phase of the trial are shown in Figure 4 as a function of cued location and opposite compatibility. Both mean correct RTs and error rates were subjected to a two-way ANOVA with cued location (above/below vs. left/right) and opposite compatibility (compatible vs. incompatible) as within-subjects variables.

As expected, there was a significant cued location effect observed between the left/right and above/below cued location conditions. In addition, there was also a significant opposite compatibility effect observed in the left/right cued location condition, but not in the above/below cued location condition.

These conclusions were supported by ANOVA. With respect to mean correct RT, there was a significant main effect of cued location,  $F(1, 31) = 37.30$ ,  $p < .001$ ,  $\eta_p^2 = .55$ , indicating that RTs were slower when “left/right” cues were shown than when “above/below” cues were shown. There was also a significant main effect of opposite compatibility,  $F(1, 31) = 26.55$ ,  $p < .001$ ,  $\eta_p^2 = .46$ , indicating that incompatible RTs were slower than compatible RTs. More importantly, there was also a significant Cued location  $\times$  Opposite compatibility interaction,  $F(1, 31) = 17.36$ ,  $p < .001$ ,  $\eta_p^2 = .40$ . Planned post hoc comparisons, with a Bonferroni-corrected critical  $p$ -value equal to .025, showed a significant effect of opposite compatibility when “left/right” cues were shown,  $t(31) = 5.12$ ,  $p < .001$ , but not when “above/below” cues were shown,  $t(31) = 2.18$ ,  $p > .025$ . All other main effects and interactions were nonsignificant.

With respect to the error rates, there was only a significant main effect of cued location,  $F(1, 31) = 29.25$ ,  $p < .001$ ,  $\eta_p^2 = .48$ , indicating that observers



**Figure 4.** Mean correct RTs (ms) and error rates (%) depicted as a function of cued location and opposite compatibility for the prime and probe phases of Experiment 2. To view this figure in colour, please see the online issue of the Journal.

committed more errors when “left/right” cues were shown than when “above/below” cues were shown. Neither the main effect of opposite compatibility effect nor the Cued location  $\times$  Opposite compatibility interaction was significant (both  $ps > .05$ ).

*Probe phase.* Note that in this, and all subsequent experiments, probe data were analysed even when an error was committed during the preceding prime phase because neither the inclusion nor exclusion of these data had any bearing on the main results. Mean correct RTs and error rates are shown in Table 2 as a function of SOA, cued location, and opposite compatibility. In addition, two other factors, prime–probe repetition and colour response repetition, were also included in the analysis. As such, both mean correct RTs and error rates were subjected to a five-way ANOVA with SOA (0 ms vs. 500 ms vs. 1000 ms vs. 1500 ms), cued location (above/below vs. left/right), opposite compatibility (compatible vs. incompatible), repetition of prime–probe opposite compatibility (repeated vs. nonrepeated), and repetition of colour response (repeated vs. nonrepeated) as within-subjects variables.

TABLE 2

Mean correct RTs (ms) and error rates (%) listed as a function of SOA, cued location, and opposite compatibility for the probe phase of Experiment 2, with error rates in parentheses

<i>SOA (ms)</i>	<i>Above/below</i>		<i>Left/right</i>	
	<i>Compatible</i>	<i>Incompatible</i>	<i>Compatible</i>	<i>Incompatible</i>
0	773 (4.43)	762 (4.25)	768 (4.43)	811 (5.10)
500	628 (5.08)	622 (4.70)	610 (3.39)	655 (5.28)
1000	569 (3.00)	591 (4.26)	568 (3.78)	598 (4.00)
1500	579 (3.78)	565 (3.14)	584 (4.05)	591 (3.59)

The cued location and opposite compatibility effects observed on the probe phase of the trial are depicted in Figure 4. Of most critical interest, the findings showed that the cued location and opposite compatibility effects were dissociated during the probe phase of the trial, consistent with the notion that the axes are computed but the endpoints of the horizontal axis remain ambiguous. More specifically, the cued location effect that is typically observed between the left/right and above/below cued location conditions was eliminated during the probe phase of the trial. Thus, the cost associated with gaining access to the horizontal axis relative to the vertical axis during the prime phase of the trial was not reincurred during the probe phase of the trial, suggesting that prior access to these axes can support priming. In contrast, the opposite compatibility effect persisted across both the prime and probe phases of the trial in the left/right cued location condition, and this effect remained nonsignificant across both phases in the above/below cued location condition.

These conclusions were supported by ANOVA. With respect to mean correct RT, there were significant main effects of SOA,  $F(3, 29) = 170.92$ ,  $p < .001$ ,  $\eta_p^2 = .95$ ; opposite compatibility,  $F(1, 31) = 8.60$ ,  $p < .01$ ,  $\eta_p^2 = .22$ ; repetition of prime–probe opposite compatibility,  $F(1, 31) = 19.75$ ,  $p < .0001$ ,  $\eta_p^2 = .39$ ; and repetition of colour response,  $F(1, 31) = 27.49$ ,  $p < .0001$ ,  $\eta_p^2 = .47$ . However, the main effect of cued location did not attain significance,  $F(1, 31) = 3.44$ ,  $p > .05$ ,  $\eta_p^2 = .10$ .

Most importantly; there was a significant Cued location  $\times$  Opposite compatibility interaction,  $F(1, 31) = 13.08$ ,  $p < .001$ ,  $\eta_p^2 = .30$ . Planned post hoc comparisons, with a Bonferroni-corrected critical  $p$ -value equal to .025, indicated a significant effect of opposite compatibility when “left/right” cues were shown,  $t(31) = 4.27$ ,  $p < .001$ , but not when “above/below” cues were shown,  $t(31) = 0.33$ ,  $p > .70$ . In addition, note that none of the higher order interactions were found to qualify the significant Cued location  $\times$  Opposite compatibility interaction. Thus, the significant Cued

location  $\times$  Opposite compatibility interaction that was associated with the probe phase of the present experiment was independent of the selection and response demands associated with the prime phase.

Furthermore, there was only one higher order interaction that qualified the nonsignificant main effect of cued location reported in the main text. In particular, there was a significant three-way interaction between cued location, repetition of prime–probe opposite compatibility, and repetition of response,  $F(1, 31) = 4.77$ ,  $p < .05$ ,  $\eta_p^2 = .13$ . Within the context of this interaction, the cued location effect could be evaluated under four (2 repetition of prime–probe opposite compatibility  $\times$  2 repetition of response) conditions. The cued location effect was found to be nonsignificant in three of the four conditions (the effect ranged in size from 8 ms to  $-1$  ms; all  $ps > .45$  or more); however, the 38 ms cued location effect was found to be significant ( $p < .0001$ ) in the one condition in which the compatibility of the opposite circle changed across the prime and probe displays, but the response remained the same. This finding was unexpected and we currently have no principled explanation for its occurrence. Given the relatively isolated, and unexpected, nature of this finding, we will continue to treat the overall nonsignificant effect of cued location observed in the probe phase of the present experiment as being relatively independent of the selection and response demands that were associated with the prime phase.

None of the main effects or interactions was found to be significant when error rates were analysed.

*Comparison of the probe and baseline conditions.* The conclusion that the cued location effect, but not the opposite compatibility effect, was significantly reduced by the present priming condition could be strengthened by demonstrating that the former effect, but not the latter, was significantly different than the corresponding effects observed in the baseline condition of Experiment 1. As expected, with respect to mean correct RT, the 12 ms cued location effect observed in the probe phase of the present experiment was found to be significantly smaller than the 52 ms cued location effect observed in Experiment 1,  $F(1, 62) = 11.59$ ,  $p < .001$ ,  $\eta_p^2 = .16$ , for the Experiment  $\times$  Cued location interaction. In contrast, the 32 ms opposite compatibility effect observed in the probe phase of the present experiment when “left/right” cues were shown was very similar to the 30 ms opposite compatibility effect observed in Experiment 1. As a result, the three-way interaction between experiment, cued location, and opposite compatibility did not approach significance,  $F(1, 62) < 1$ .

Similar findings were obtained when error rates were compared across the two experiments. There was significant Experiment  $\times$  Cued location interaction,  $F(1, 62) = 13.18$ ,  $p < .001$ ,  $\eta_p^2 = .18$ , indicating that cued location effect

was smaller during the probe phase of the present experiment ( $M = 0.10\%$ ) than it was in Experiment 1 ( $M = 2.16\%$ ). In contrast, the three-way interaction between experiment, cued location, and opposite compatibility did not approach significance,  $F(1, 62) < 1$ .

In summary, the results of Experiment 2 provided initial support for the hypothesis that the disambiguation of “left/right” cues depends on the mode of spatial orienting. In Experiment 2, observers generated a spatially directed shift of visual attention in response to a spatial word cue during the prime phase of the trial. As expected, the magnitude of the cued location effect observed during the probe phase of Experiment 2 was significantly reduced relative to the magnitude of this effect observed in the baseline condition of Experiment 1. More importantly, the magnitude of the opposite compatibility effect observed during the probe phase of Experiment 2 persisted and was similar to the magnitude observed in the baseline condition of Experiment 1. This finding is consistent with the hypothesis that the meaning of “left” and “right” is not fully resolved when these cues are used to control shifts of visual attention.

### EXPERIMENT 3

Experiment 3 investigated whether “left/right” cues require greater disambiguation when they are used to control less divisible, more discrete, modes of orienting such as manual pointing. Experiment 3 was therefore identical to Experiment 2, except that a spatially directed arm movement was performed in response to a spatial word cue during the prime phase of the trial. As when spatially directed shifts of visual attention are generated in response to spatial words cues, we expected that pointing RTs would also be slower when “left/right” cues were shown than when “above/below” cues were shown, again signifying slower access to the horizontal axis. In addition, we also expected that manual pointing responses would require greater disambiguation of the endpoints of the horizontal axis before being executed; consequently, we expected participants to commit relatively few directional errors in response to “left/right” cues during the prime phase of this experiment. Note that in the previous two experiments (see also, Gibson et al., 2009), failure to adequately disambiguate the endpoints of the horizontal axis was signalled by a significant opposite compatibility effect. Unfortunately, this same empirical outcome could not be used to evaluate the extent to which the endpoints of the horizontal axis were resolved during the prime phase of the present experiment because the colours of the circles surrounding the spatial word cues were not relevant for generating the spatially directed pointing response. Instead, failure to adequately disambiguate the endpoints of the horizontal axis during the

prime phase of the present experiment could only be evaluated by measuring the proportion of opposite pointing responses (e.g., pointing to the left location in response to a “right” cue).

The probe phase of the trial began immediately following the pointing response and was identical to Experiments 1 and 2. Of particular interest in this experiment was whether the computations underlying the prior spatially directed pointing response could influence the magnitude of the cued location and opposite compatibility effects observed when a spatially directed shift of visual attention was generated during the probe phase. If spatially directed pointing requires greater disambiguation of the endpoints of the horizontal axis, and if these prior computations can transfer to other modes of orienting, then the opposite compatibility effect observed during the probe phase of this experiment should be significantly reduced relative to the opposite compatibility effect observed during the baseline condition of Experiment 1.

## Method

*Participants.* Thirty-two new University of Notre Dame undergraduates participated to partially fulfil a course requirement. All participants reported normal or corrected-to-normal acuity and normal colour vision.

*Stimuli and apparatus.* The stimuli and apparatus were identical to those used in Experiment 1 with the sole exception being that a joystick was built into the response box. Note that the response box was placed directly underneath the chinrest and the experiment was conducted in a dimly lit room, making it unlikely that observers could see their pointing responses, though they could sense them kinaesthetically. The joystick was configured to record binary responses (either left/right or above/below).

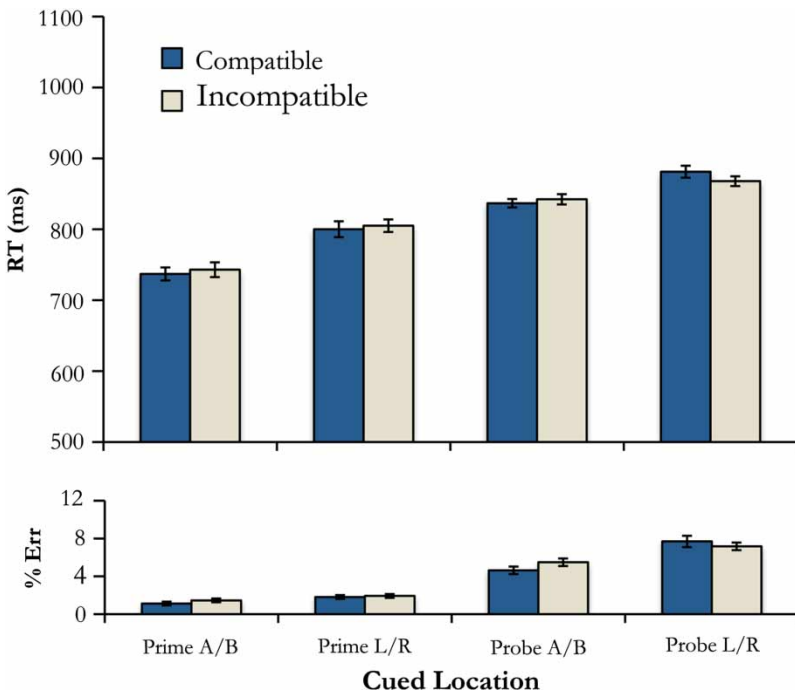
*Procedure and design.* The procedure used during the prime phase of the trial was identical to the procedure used in Experiment 2 with the sole exception being that observers were asked to move the joystick in accordance with the direction indicated by the spatial word cue as quickly and as accurately as possible using their left arm. The joystick response was recorded as “correct” when observers moved the lever in the cued direction; all other responses were recorded as “incorrect”. The probe phase of the trial began immediately following the joystick response. The procedure used during the probe phase of the trial was identical to the procedure used in Experiment 2 with the sole exception being that observers now responded to the colour of the target using the middle and index fingers of their right hand. Observers always used their index finger to respond “red” and their middle finger to respond “green”. There were a total of 768 experimental trials (each with two

responses) that were preceded by 16 practice trials. A different random order was presented to each observer.

## Results and discussion

*Prime phase.* Mean correct RTs and error rates obtained during the prime phase of the trial are shown in Figure 5 as a function of cued location and opposite compatibility. Both mean correct RTs and error rates were subjected to a two-way ANOVA with cued location (above/below vs. left/right) and opposite compatibility (compatible vs. incompatible) as within-subjects variables.

As expected, there was a significant cued location effect observed between the left/right and above/below cued location conditions when mean correct RTs were analysed. In addition, recall that the opposite compatibility effect was not expected during the prime phase of the trial because the colours of the circles surrounding the spatial word cue were not relevant for generating a spatially directed pointing response. The findings were consistent with this



**Figure 5.** Mean correct RTs (ms) and error rates (%) depicted as a function of cued location and opposite compatibility for the prime and probe phases of Experiment 3. To view this figure in colour, please see the online issue of the Journal.

expectation. Moreover, error rates were also found to be low and approximately equal in both the above/below (1.29%) and left/right (1.87%) cued location conditions. This finding is important because it suggests that the endpoints of both axes were equally disambiguated.

These conclusions were supported by ANOVA. With respect to mean correct RT, there was a significant main effect of cued location,  $F(1, 31) = 11.03$ ,  $p < .005$ ,  $\eta_p^2 = .26$ , indicating that RTs were slower when “left/right” cues were shown than when “above/below” cues were shown. However, neither the main effect of opposite compatibility, nor the Cued location  $\times$  Opposite compatibility interaction approached significance during the prime phase of the trial (both  $ps > .30$ ). In addition, no significant effects were observed when the error rate data were analysed (all  $ps > .10$ ).

*Probe phase.* Mean correct RTs and error rates are shown in Table 3 as a function of SOA, cued location, and opposite compatibility. Both mean correct RTs and error rates were subjected to a three-way ANOVA with SOA (0 ms vs. 500 ms vs. 1000 ms vs. 1500 ms), cued location (above/below vs. left/right), and opposite compatibility (compatible vs. incompatible) as within-subjects variables.

The cued location and opposite compatibility effects observed during the probe phase of the trial are depicted in Figure 5. As expected, the opposite compatibility effect was eliminated during the probe phase of Experiment 3. However, the cued location effect unexpectedly persisted during the probe phase of the trial. Such findings suggest that the reference frame computations that underlie spatially directed pointing responses can facilitate access to the left and right cued locations that are specified for spatially directed shifts of visual attention, even though the axes on which those locations are based do not appear to support priming. Although the present findings are counterintuitive, we will show in the General Discussion that these findings can in fact be explained within a framework that distinguishes between supramodal and domain-specific frames of reference.

TABLE 3  
Mean correct RTs (ms) and error rates (%) listed as a function of SOA, cued location, and opposite compatibility for the probe phase of Experiment 3, with error rates in parentheses

SOA (ms)	Above/below		Left/right	
	Compatible	Incompatible	Compatible	Incompatible
0	1021 (5.48)	1002 (6.08)	1058 (8.60)	1032 (9.33)
500	815 (5.99)	826 (5.68)	849 (7.56)	856 (7.50)
1000	748 (3.26)	776 (5.22)	829 (8.48)	808 (6.53)
1500	763 (3.80)	765 (4.96)	788 (6.13)	776 (5.31)

These conclusions were supported by ANOVA. With respect to mean correct RT, there were significant main effects of SOA,  $F(3, 29) = 142.01$ ,  $p < .001$ ,  $\eta_p^2 = .94$ , and cued location,  $F(1, 31) = 10.80$ ,  $p < .005$ ,  $\eta_p^2 = .26$ . Neither the main effect of opposite compatibility, nor the Cued location  $\times$  Opposite compatibility interaction approached significance during the probe phase of the trial (both  $ps > .10$ ). The only significant effects observed in the error rate data were the main effects of SOA,  $F(3, 29) = 3.11$ ,  $p < .05$ ,  $\eta_p^2 = .24$ , and cued location,  $F(1, 31) = 20.22$ ,  $p < .001$ ,  $\eta_p^2 = .40$ .

*Evaluation of an alternative spatial interference account.* As mentioned in Experiment 1, previous studies have shown that cue direction does not interact with keypress response (Gibson & Kingstone, 2005). However, the procedure used in Experiment 3 was different than the procedure used in previous studies in that participants were required to execute two motor responses on each trial in Experiment 3: A joystick response (using their left hand) during the prime phase and a keypress response (using the index and middle fingers of their right hand) during the probe phase. Could the significant cued location effect observed during the probe phase of Experiment 3 be due to spatial interference arising from these two motor responses? In particular, keypress responses made during the probe phase may be significantly slower in the left/right cued location condition than in the above/below cued location condition because, on half the trials in the left/right cued location condition, the joystick responses made during the prime phase were incompatible with the keypress responses made during the probe phase (i.e., the joystick was moved to the right in response to “right” cues during the prime phase followed by a left key response to report “red” during the probe phase, or vice versa).

In order to examine this question, we compared keypress responses made during the probe phase under three response repetition conditions: The direction compatible condition (joystick response = “left/right”; keypress response = “left/right”); the direction incompatible condition (joystick response = “left/right”; keypress response = “right/left”); and the direction orthogonal condition (joystick response = “above/below”; keypress response = “left/right” or “right/left”). Note that in each of these conditions, the joystick response corresponds to the cued location condition. If the cued location effect observed in Experiment 3 is due to spatial interference arising from incompatible directional responses, then RT should be significantly slower in the direction incompatible condition than in either the direction compatible or direction orthogonal conditions. However, the results were clearly inconsistent with this prediction. Mean correct RT in each of the direction compatible, direction incompatible, and direction orthogonal conditions was observed to be 729 ms, 730 ms, and 696 ms, respectively. Furthermore, the direction compatible and direction incompatible conditions

were not significantly different from one another ( $p > .90$ ); and both of these left/right cued location conditions were significantly slower than the direction orthogonal condition (i.e., the above/below cued location condition; both  $ps < .005$ ). Similar findings were observed when error rates were analysed. Overall, these findings suggest that the cued location effect observed in Experiment 3 is due to differences in the processing of left/right vs. above/below cued locations and not to differences in spatial interference arising from the presence of directionally incompatible responses in the left/right cued location condition.

*Comparison of the probe and baseline conditions.* The conclusion that the opposite compatibility effect, but not the cued location effect, was significantly reduced by the present priming condition could be strengthened by demonstrating that the former effect, but not the latter, was significantly different than the corresponding effects observed in the baseline condition of Experiment 1. As expected, with respect to mean correct RT, the  $-13$  ms opposite compatibility effect observed in the probe phase of the present experiment when “left/right” cues were shown was significantly smaller than the  $30$  ms opposite compatibility effect observed in Experiment 1,  $F(1, 62) = 8.82$ ,  $p < .005$ ,  $\eta_p^2 = .12$ , for the Experiment  $\times$  Cued location  $\times$  Opposite compatibility interaction. In contrast, the  $35$  ms cued location effect observed in the probe phase of the present experiment was similar to the  $52$  ms cued location effect observed in Experiment 1. As a result, there was a significant main effect of cued location,  $F(1, 62) = 35.88$ ,  $p < .001$ ,  $\eta_p^2 = .37$ , but the Experiment  $\times$  Cued location interaction did not approach significance,  $F(1, 62) = 1.45$ ,  $p > .20$ ,  $\eta_p^2 = .02$ .

Similar findings were obtained when error rates were compared across the two experiments. There was a marginally significant Experiment  $\times$  Cued location  $\times$  Opposite compatibility interaction,  $F(1, 62) = 3.03$ ,  $p = .087$ ,  $\eta_p^2 = .05$ . In contrast, the two-way interaction between experiment and cued location did not approach significance,  $F(1, 62) < 1$ , though the main effect of cued location was significant,  $F(1, 62) = 42.40$ ,  $p < .001$ ,  $\eta_p^2 = .41$ .

In summary, observers generated a spatially directed movement of the arm in response to a spatial word cue during the prime phase of Experiment 3. As expected, the magnitude of the opposite compatibility effect observed during the probe phase of the trial was significantly reduced relative to the magnitude of this effect observed in the baseline condition of Experiment 1. This finding is consistent with the hypothesis that “left/right” cues receive greater disambiguation when they are used to control less divisible, more discrete, modes of orienting such as manual pointing. However, unlike the opposite compatibility effect, the cued location effect persisted during the probe phase of Experiment 3. This unexpected finding will be given further consideration

in the General Discussion, but first we will consider one alternative explanation.

## EXPERIMENT 4

The purpose of Experiment 4 was to test an assumption underlying the present repetition priming paradigm. In Experiments 2 and 3, observers were instructed to orient in accordance with the spatial word cue during both the prime and probe phases of the experiment. The purpose of the orienting response executed during the prime phase of the trial was to potentially facilitate the reference-frame computations that occur when spatially directed shifts of visual attention are generated in response to spatial word cues during the probe phase of the trial. However, it is also possible that observers exclusively used the orienting response generated during the prime phase as the directional cue during the probe phase. This may have been particularly true in Experiment 3 where observers translated the spatial word cue into an overt, spatially directed pointing response during the prime phase of the trial. Indeed, Gibson et al. (2009) have shown that other visually based “pointing cues” such as arrows do not typically elicit the opposite compatibility effect. In this view, the elimination of the opposite compatibility effect observed in Experiment 3 might not reflect the priming of directional computations so much as it reflects the use of different directional cues. However, it is doubtful that this alternative explanation can account for the full pattern of results observed in Experiment 3 because Gibson et al. (2009; see Gibson & Kingstone, 2006) have also shown that pointing cues do not typically elicit the cued location effect either.

Nevertheless, we considered it prudent to test this alternative hypothesis in Experiment 4 by using an arrow cue instead of the spatial word cue to direct orienting. Arrow cues were chosen for this experiment because these cues were not expected to elicit either of the two costs associated with spatial word cues when used on their own (Gibson & Kingstone, 2006; Gibson et al., 2009). In particular, if observers use the arrow cue to direct both orienting responses, then no cued location or opposite compatibility effects should be observed during both the prime and probe phases of the present experiment. If this result is obtained, then we can be reasonably assured that the differential results obtained across the probe phases of Experiments 3 and 4 derived from the use of the initial cue (in interaction with the prime) because this was the only difference between the two experiments. However, if the results reported in Experiment 3 were obtained because observers routinely and exclusively used the overt pointing response (as opposed to the spatial word cue) to direct visual attention during the probe phase; and, if overt pointing responses can produce a cued location effect (which they must if

this account is to explain the results obtained in Experiment 3), then we should expect the same results observed during the probe phase of Experiment 3: Namely, a significant cued location effect should be observed during the probe phase of the trial.

## Method

*Participants.* Thirty-six new University of Notre Dame undergraduates participated to partially fulfil a course requirement. All participants reported normal or corrected-to-normal acuity and normal colour vision.

*Stimuli and apparatus.* The stimuli and apparatus were identical to those used in Experiment 3 with the sole exception being that an arrow cue appeared instead of a spatial word cue. The arrow cues subtended  $0.48^\circ \times 1.18^\circ$  of visual angle and appeared at each of four orientations relative to the observer:  $\uparrow$ ,  $\downarrow$ ,  $\leftarrow$ , and  $\rightarrow$ .

*Procedure and design.* The procedure was identical to the procedure used in Experiment 3 with the sole exception being that an arrow cue appeared instead of a spatial word cue (see Figure 2C).

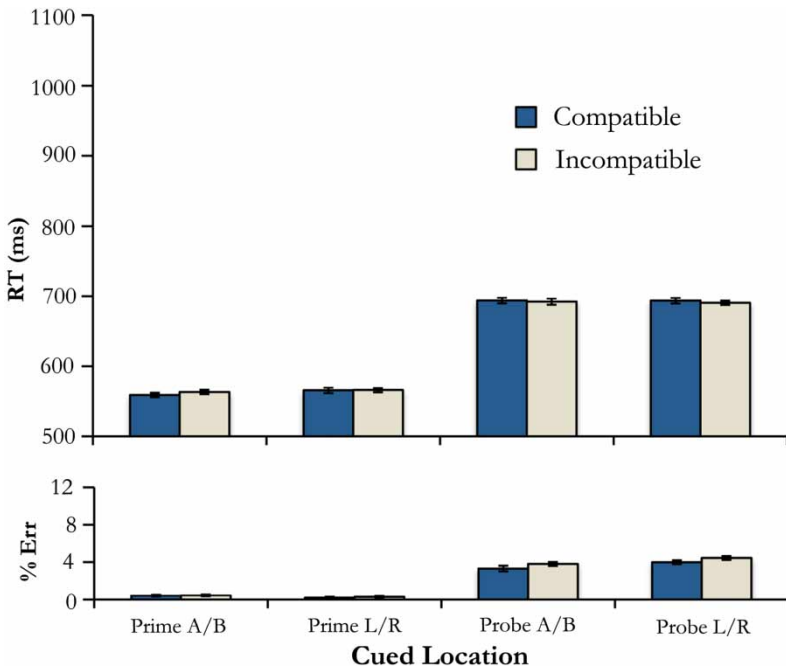
## Results and discussion

*Prime phase.* Mean correct RTs and error rates obtained during the prime phase of the trial are shown in Figure 6 as a function of cued location and opposite compatibility. Both mean correct RTs and error rates were subjected to a two-way ANOVA with cued location (above/below vs. left/right) and opposite compatibility (compatible vs. incompatible) as within-subjects variables.

As expected, neither the cued location effect, nor the opposite compatibility effect was found to be significant when arrow cues were shown (all  $ps > .35$  for mean correct RTs, and all  $ps > .05$  for error rates).

*Probe phase.* Mean correct RTs and error rates are shown in Table 4 as a function of SOA, cued location, and opposite compatibility. Both mean correct RTs and error rates were subjected to a three-way ANOVA with SOA (0 ms vs. 500 ms vs. 1000 ms vs. 1500 ms), cued location (above/below vs. left/right), and opposite compatibility (compatible vs. incompatible) as within-subjects variables.

The cued location and opposite compatibility effects observed during the probe phase of the trial are depicted in Figure 6. The present findings were consistent with the assumption that observers routinely used the initial spatial cue to direct their orienting responses during both the prime phase and the probe phase of the trial. Thus, the selective modulation of



**Figure 6.** Mean correct RTs (ms) and error rates (%) depicted as a function of cued location and opposite compatibility for the prime and probe phases of Experiment 4. To view this figure in colour, please see the online issue of the Journal.

the cued location and opposite compatibility effects observed during the probe phases of Experiments 2 and 3 can be interpreted as priming of the reference-frame computations that occurred when observers directed their visual attention in accordance with the initial spatial word cues.

These conclusions were supported by ANOVA. With respect to mean correct RTs, there was only a significant main effect of SOA,  $F(3, 33) = 182.32$ ,

TABLE 4

Mean correct RTs (ms) and error rates (%) listed as a function of SOA, cued location, and opposite compatibility for the probe phase of Experiment 4, with error rates in parentheses

SOA (ms)	<i>Above/Below</i>		<i>Left/Right</i>	
	<i>Compatible</i>	<i>Incompatible</i>	<i>Compatible</i>	<i>Incompatible</i>
0	852 (2.85)	856 (4.13)	855 (5.68)	846 (5.69)
500	667 (3.48)	666 (4.12)	670 (3.83)	672 (5.16)
1000	628 (2.91)	640 (3.29)	628 (3.16)	635 (3.45)
1500	626 (4.01)	605 (3.66)	619 (3.30)	607 (3.44)

$p < .001$ ,  $\eta_p^2 = .94$ , indicating that RTs decreased as SOA increased. None of the other main effects or interactions was significant (all  $ps > .10$ ). In particular, note that RTs were nearly identical in both the above/below ( $M = 693$  ms) and left/right ( $M = 692$  ms) cued location conditions. Similar findings were obtained when error rates were analysed.

*Comparison of arrow and word cues.* The conclusion that observers routinely used the initial spatial cue to direct their orienting responses during both the prime phase and the probe phase of the trial could be strengthened by demonstrating that the cued location effect observed in Experiment 3 (when spatial word cues were shown) was significantly larger than the cued location effect observed in the present experiment (when arrow cues were shown). As expected, with respect to mean correct RT, the  $-1$  ms cued location effect observed in the probe phase of the present experiment was significantly smaller than the 35 ms cued location effect observed in Experiment 3,  $F(1, 66) = 10.32$ ,  $p < .005$ ,  $\eta_p^2 = .14$ , for the Experiment  $\times$  Cued location interaction. Likewise, with respect to error rates, the 0.66% cued location effect observed in the probe phase of the present experiment was significantly smaller than the 2.37% cued location effect observed in Experiment 3,  $F(1, 66) = 9.70$ ,  $p < .005$ ,  $\eta_p^2 = .13$ , for the Experiment  $\times$  Cued location interaction. Hence, these significant interactions must be attributed to the use of different spatial cues because the two experiments were otherwise identical.

In summary, the findings obtained in Experiment 4 were consistent with the assumption that observers routinely used the initial spatial cue to direct their orienting responses during both the prime phase and the probe phase of the trial. In addition, it should also be noted that these findings also help to rule out the spatial interference account considered in Experiment 3. If the cued location effect observed in Experiment 3 was due to spatial interference arising from the presence of directionally incompatible responses in the left/right cued location, then a similar cued location effect should have also been observed in Experiment 4 because participants made the same number of directionally incompatible responses in the left/right cued location condition in this experiment as they did in Experiment 3.

## GENERAL DISCUSSION

In the present study, we hypothesized that the resolution of preestablished semantic ambiguities associated with “left” and “right” may vary depending on the modality of spatial orienting. In particular, we hypothesized that these ambiguities may not be fully resolved when “left” and “right” are used to control visual attention because attention can be divided across the two

endpoints of the horizontal axis simultaneously. In contrast, other modes of orienting such as manual pointing cannot be divided across multiple locations simultaneously. Consequently, spatially directed pointing responses may require stronger disambiguation of the endpoints of the horizontal axis than spatially directed shifts of visual attention before they are generated in response to “left/right” cues.

The hypothesized contingency between the dynamics of semantic resolution and the modality of orienting was investigated within the context of a repetition priming paradigm. In this paradigm, the effects of prior orienting responses were measured on subsequent, spatially directed shifts of visual attention. On each trial, both the prime and probe orienting responses were generated in response to a spatial cue that was maintained across the duration of each trial. Experiment 4 provided evidence that observers did in fact direct their visual attention in accordance with the spatial cues during the probe phase of each trial (as opposed to the prior orienting responses generated during the prime phase of each trial). Thus, any modulation of the cued location or opposite compatibility effects observed during the probe phase of the trial as a result of the orienting responses generated during the prime phase of the trial can be interpreted as reflecting modulations of the reference-frame computations that typically occur when observers direct their visual attention in accordance with these cues.

Experiment 2 investigated whether the endpoints of the horizontal axis remain at least partially ambiguous when spatial terms such as “left” and “right” are used to direct shifts of visual attention. This was accomplished by measuring the magnitude of the cued location and opposite compatibility effects observed during the probe phase when a prior spatially directed shift of visual attention was generated during the prime phase. On these trials, we hypothesized that the horizontal and vertical axes would be computed during the prime phase in response to “left/right” cues, but we also hypothesized that the endpoints of the horizontal axis would remain unresolved in this condition. Consequently, we expected that these prior computations would facilitate access to the horizontal axis, but not disambiguation of the endpoints of this axis, during the probe orienting response. That is, we expected these prior computations to significantly reduce the magnitude of the cued location effect, but not the opposite compatibility effect, relative to the baseline condition. This is precisely what we found in Experiment 2. Moreover, this pattern of findings could not be attributed to potential artifacts arising from the repetition of prime–probe displays, or the repetition of colour responses. Thus, the present findings are consistent with the notion that the endpoints of the horizontal axis remain at least partially ambiguous when “left” and “right” cues are used to direct shifts of visual attention.

Experiment 3 investigated whether the endpoints of the horizontal axis would be more fully disambiguated when a manual pointing response was

generated during the prime phase in response to “left/right” cues. If so, then we expected the prior computation of axes and endpoints during the prime phase in which a spatially directed pointing response was generated to significantly reduce the magnitude of the cued location and opposite compatibility effects observed during the probe phase in which a spatially directed shift of visual attention was generated. The results of Experiment 3 provided partial support for these predictions. Most importantly, the results showed that the magnitude of the opposite compatibility effect was significantly reduced relative to the baseline, providing critical evidence that the endpoints of the horizontal axis were disambiguated when “left” and “right” cues were used to direct movements of the arm. Surprisingly, the results also showed that the magnitude of the cued location effect was not significantly reduced relative to the baseline; furthermore, this effect could not be attributed to spatial interference arising from the execution of directionally incompatible responses across the prime and probe displays when “left/right” cues were shown.

Note, however, that although it is possible for axes to be computed independent of endpoints (see, e.g., Landau & Hoffman, 2005; McCloskey, 2009; McCloskey et al., 1995, for relevant neuropsychological evidence), it may not be possible for endpoints to be computed independent of axes. Indeed, the endpoints of an axis seemingly cannot be defined in the absence of an axis. Hence, the apparent dissociation observed in Experiment 3 should not be interpreted as showing that endpoints can be computed independent of their constituent axes. How, then, can the processing of direction (endpoints) that underlies one type of orienting response selectively influence the processing of direction that underlies another orienting response without also influencing the processing of the underlying axes, as appeared to occur in Experiment 3?

The answer, we believe, requires distinguishing between a supramodal frame of reference and domain-specific frames of reference, together with a transduction process that is responsible for translating supramodal spatial information into domain-specific directional orienting responses (and vice versa). For instance, consider the baseline condition depicted in Figure 2A in which the “left” word cue is presented. We assume that this cue is initially identified in such a way that the meaning of “left” can be represented within a supramodal frame of reference that may be used to direct a variety of different orienting responses to the appropriate observer-centred location in space, including directing a shift of visual attention or a movement of the arm (see Soechting & Flanders, 1992, for a review). Note, however, that the reference frame computations that underlie the encoding of “left” into this supramodal representation do not appear to be the same as the reference frame computations that are required when this supramodal spatial information is translated into a specific orienting response. Recall that the

cued location and opposite compatibility effects were both observed in the baseline condition of Experiment 1, even though visual attention was shifted only after the word cues had been comprehended and presumably maintained within a supramodal frame of reference. Such findings were interpreted to suggest that both the cued location and opposite compatibility effects are not merely one-time costs associated with the initial comprehension of the spatial terms, but rather reflect costs that accrue when the spatial concepts conveyed by these spatial terms are translated into specific orienting responses (see also, Logan, 1995). At the very least, this translation appears to require the transformation of “left” from the supramodal frame of reference to a domain-specific frame of reference that is suitable for controlling a particular mode of orienting.

In addition, just as the meaning of “left” can be translated from the supramodal frame of reference to a domain-specific frame of reference that is suitable for controlling a particular mode of orienting, we also propose that the meaning of “left” can be translated from a domain-specific frame of reference back to the supramodal frame of reference. In other words, the supramodal meaning of “left” may be influenced by domain-specific modes of orienting. In this way, the endpoints of the supramodal horizontal axis may become more fully resolved following a movement of the arm than following a shift of visual attention. Furthermore, once the supramodal meaning of “left” has been refined in this manner, this representation may then be used to influence other modes of orienting.

With the distinction between supramodal and domain-specific frames of reference in mind, it is now possible to explain why axial (but not endpoint) priming was observed in Experiment 2, whereas endpoint (but not axial) priming was observed in Experiment 3. Specifically, axial priming may have occurred in Experiment 2 because the same spatially directed shift of visual attention was generated across the prime and probe displays. As such, the domain-specific computations that were generated during the prime phase of the trial could facilitate the same domain-specific computations that were generated during the probe phase of the trial. Indeed, the domain-specific axes that were computed during the prime phase could have simply been translated from one reference object to another in Experiment 2. Moreover, differential endpoint priming was not observed in Experiment 2 because, by hypothesis, shifts of visual attention do not require the endpoints of the horizontal axis to be fully resolved. Consequently, direction remained unresolved in both the domain-specific and supramodal representations; and, to the extent that endpoint priming occurred within the domain-specific pathway, both endpoints were likely primed (or maintained) in Experiment 2.

In contrast, axial priming may not have occurred in Experiment 3 because the prime response (manual pointing of the arm) occurred within a different domain-specific pathway than the probe response (shift of visual attention).

However, although these domain-specific reference frame computations could not directly influence each other, prior movements of the arm could influence subsequent shifts of visual attention indirectly by disambiguating the meaning of “left” and “right” within the supramodal representation of space. Thus, in this view, pointing does not enhance the focus of visual attention by directly facilitating the computation of endpoints within visual attention’s domain-specific pathway; rather, pointing enhances the focus of visual attention by disambiguating the meaning of “left” and “right” within a supramodal representation of space that in turn affects how endpoints are translated within visual attention’s domain-specific pathway. This account may therefore explain how directional movements of the arm can selectively influence directional shifts of visual attention without also influencing the processing of the underlying axes.

In considering putative interactions between supramodal and domain-specific frames of reference, it should be noted that the transition from one mode of orienting to another may incur significant costs if the spatial information encoded within one domain-specific frame of reference is routinely translated into another domain-specific frame of reference via the supramodal frame of reference. In addition, other transitions that occurred in Experiment 3 such as the transition from one task (direction discrimination) to another (colour discrimination), as well as the transition from one response mode (joystick) to another (keypress), may also incur significant costs. Indeed, the probe-task RTs in Experiment 3, where movements of visual attention followed movements of the arm, were found to be significantly slower overall (by approximately 133 ms) than the probe-task RTs in Experiment 1, where movements of visual attention did not follow any prior movements. Regardless of the source of this RT cost, it is important to consider whether any of these transition costs might have contributed to either the nonsignificant opposite compatibility effect or the significant cued location effect that was observed in Experiment 3.

For instance, suppose the opposite distractor did cause significant interference in Experiment 3, but this interference dissipated during the period of time incurred by the transition cost. Note, however, that we considered this alternative explanation of the nonsignificant opposite compatibility effect observed in Experiment 3 to be unlikely because the interference that arises from incompatible distractors actually *increases* as RT increases (Lavie & de Fockert, 2003). Indeed, Gibson et al. (2009) observed a linear increase in the magnitude of the opposite compatibility effect when they measured this effect across the entire RT distribution. In other words, the magnitude of the opposite compatibility effect was smallest (but still significant) for the fastest RTs and grew in magnitude as RTs increased, presumably because observers were exposed to the distractor for longer durations as RT increased.

Nevertheless, if significant interference arising from the opposite distractor did dissipate during the period of time incurred by the transition cost in Experiment 3, then that interference may still be detected on those trials in which observers happened to respond quickly. We examined this issue in the present context by first creating cumulative RT percentiles for each individual; and, then we examined the magnitude of the opposite compatibility effect in those RT bins in which the mean value across individuals in each of the compatible and incompatible conditions was less than or equal to the corresponding mean correct RTs in Experiment 2 (in which a significant opposite compatibility effect was observed). However, contrary to this alternative account, the opposite compatibility effect did not approach significance in any of the RT bins that fell in the critical range—the three fastest cumulative RT percentiles; in fact, the numerical value of this effect was actually found to be in the opposite direction ( $-9$  ms,  $-17$  ms, and  $-19$  ms across the three fastest cumulative percentiles, respectively). Similar findings were observed across the other cumulative percentiles.

Next, suppose the significant cued location effect observed in Experiment 3 was due to a larger transition cost incurred in the left/right cued location condition than in the above/below cued location condition. However, this alternative explanation of the cued location effect also seems unlikely because probe–task RTs in Experiment 3 were found to be slowed equally across the two cued location conditions relative to the probe–task RTs in Experiment 1. Thus, neither the nonsignificant opposite compatibility effect, nor the significant cued location effect observed in Experiment 3 appears to be a simple artifact of slower RTs incurred by the transition cost.

In addition, it is also important to note that although the present pattern of findings appears to suggest that a rather indirect relation between movements of the arm and movements of attention, this conclusion need not be inconsistent with other accounts that have proposed a much more direct relation between these two modes of orienting. For instance, according to the premotor theory of attention (Eimer et al., 2005; Rizzolatti et al., 1994), the control of spatially directed limb movements and spatially directed shifts of attention are closely linked such that shifts of attention are elicited whenever motor responses are executed or prepared.

Consider the findings reported by Gherri et al. (2009). In their experiment, left and right arrows were used to cue the direction of an arm movement; during the response preparation interval, irrelevant visual probe stimuli occasionally appeared near either the cued location of the hand or the current location of the hand, and the N1 ERP component, which indexes attentional modulation, was measured. The results showed that the N1 component was enhanced when the visual probe appeared near the cued location of the hand, but no enhancement was observed when the visual

probe appeared near the current location of the hand. In contrast, the opposite pattern of findings was obtained when the cue was interpreted to indicate which hand to move (as opposed to which direction to move). Such findings are important because they suggest that the intention to execute a directional arm movement can also elicit an automatic shift of visual attention to corresponding locations.

However, if the intention to execute a directional arm movement elicits an automatic shift of visual attention to the cued location of the arm, then participants in the present study may have also shifted their visual attention to the cued location of the arm during the prime phase of Experiment 3 in which a spatially directed movement of the arm was required. Furthermore, if such shifts of visual attention occurred, then it may be reasonable to expect that domain-specific axial priming should also have been observed during the probe phase of Experiment 3 just as it was in Experiment 2; that is, the cued location effect should have been significantly reduced in Experiment 3 relative to the baseline, but it was not.

However, although the present findings appear to be discrepant with the findings reported by Gherri et al. (2009), it is likely that shifts of visual attention that are elicited as a result of an arm movement are encoded within a different frame of reference than shifts of visual attention that are elicited without an arm movement. For instance, Reed, Grubb, and Steele (2006) have suggested that visual attention may interact with the somatosensory system via limb-centred frames of reference. Consequently, shifts of visual attention that are elicited as a result of an arm movement may be encoded within an arm-centred frame of reference wherein relations such as left and right are specified relative to the arm, whereas shifts of visual attention that are elicited without an arm movement may be encoded within a different (e.g., retina-centred or head-centred) frame of reference. Thus, shifts of visual attention may have been elicited as a result of the spatially directed pointing response generated during the prime phase of Experiment 3 without giving rise to axial priming during the probe phase of Experiment 3 because the two successive shifts of visual attention were encoded within different frames of reference. Hence, the successive computation of axes within the same domain-specific pathway may not be sufficient for producing axial priming unless these axes are encoded within the same frame of reference.

In addition, the distinction between supramodal and domain-specific frames of reference also helps clarify what it means for two modes of orienting to share a common frame of reference. For instance, Bekkering and Pratt (2004) have concluded that spatially directed movements of the arm and shifts of visual attention both utilize the same frames of reference based on evidence suggesting that both modes of orienting appear to be sensitive to the same space-based and object-based manipulations. However, as the present study

has shown, two modes of orienting may be sensitive to the same reference frame manipulations without necessarily relying on the same domain-specific frames of reference.

More specifically, recall that spatially directed movements of the arm and shifts of visual attention were both found to be affected similarly by cued location (above/below vs. left/right) during the prime phase of Experiments 2 and 3, suggesting that both relied on domain-specific frames of reference in which the horizontal axis was more difficult to access than the vertical axis. This finding suggests that there may well be many similarities between the processing dynamics of these two reference-frame systems that will lead them to be similarly affected by various experimental manipulations. Yet, the findings obtained in Experiment 3 suggested that this particular similarity was not sufficient for priming the cued location effect across the two orienting responses, even though the findings obtained in Experiment 2 suggested that the cued location effect could be primed when the two orienting responses (and presumably the two domain-specific reference-frame systems) were identical. Thus, the occurrence of axial priming may represent a stronger criterion for assessing whether two modes of orienting share the same domain-specific frame of reference. Based on this evidence, the present study has concluded that spatially directed movements of the arm and spatially directed shifts of visual attention do not share the same domain-specific frame of reference, though these two modes of orienting are capable of interacting indirectly via the supramodal frame of reference.

The endpoint priming observed in Experiment 3 was interpreted to suggest that the meaning of “left” and “right” was disambiguated when these terms were grounded in the motor system. As a result, subsequent shifts of visual attention could be more focused along the horizontal axis when they followed directional movements of the arm. These findings are important because they provide further evidence that spatial concepts have functional consequences for orienting (Gibson & Kingstone, 2006; Gibson et al., 2009; Logan, 1995); but even more critically, these findings are important because they provide evidence that our actions can also influence the semantics of space.

As such, the present findings are relevant to current theories proposing that semantic knowledge is grounded in the brain’s modal systems for perception, action, and affect (see Barsalou, 2008, for a comprehensive review). For instance, previous studies have revealed activation in the head, arm, and leg areas of the motor cortex when participants read corresponding action verbs (Pulvermüller, 2005). Such evidence has been interpreted to suggest that the meaning of action verbs is linked to simulations, or reenactments, of motor states that were acquired during experiences in which the action verbs were performed.

In this view, the meaning of spatial terms such as “left” and “right” may be linked to simulations, or reenactments, of perceptual and motor states that

were acquired during discourse contexts in which these terms were encountered. In the case of “left” and “right”, these prior experiences likely involve a variety of inconsistent perceptual and motor states encountered across different contexts, leading to the preestablished semantic ambiguities associated with these terms (Gibson et al., 2009). However, as the present study has shown these concepts can be disambiguated, at least temporarily, when they are enacted by directional motor actions. Whether the motor enactments of “left” and “right” that were exhibited during the prime phase of Experiment 3 were also reenacted (or simulated) during the ensuing probe phase cannot be determined by the present findings. What is known is that “left” and “right” did not appear to be simply equated with the directional pointing responses that were enacted during the prime phase. Had these spatial terms been simply equated with the directional pointing responses, then the results obtained in Experiment 3 should have been identical to the results obtained in Experiment 4 in which directional arrow cues were shown because the same directional motor responses were enacted in both experiments.

Thus, although directional motor responses influenced the meaning of “left” and “right” by disambiguating the endpoints of the horizontal axis, these responses did not exhaust the spatial meaning of these terms. Rather, it was still more difficult to access the horizontal axis when “left” and “right” cues were shown than when “←” and “→” cues were shown, even when their respective endpoints could be equally discriminated, suggesting that the spatial concepts associated with “left” and “right” remained different than the spatial concepts associated with “←” and “→” (see also Gibson & Kingstone, 2006; Gibson et al., 2009). Further examination of this difference is therefore warranted and should further clarify the structure of spatial concepts.

In conclusion, the results of the present study have demonstrated that grounding spatial language in the motor system can enhance the focus of visual attention by disambiguating the endpoints of the horizontal axis. In so doing, the present study has extended previous research demonstrating that spatial semantics can influence the spatial distribution of attention by demonstrating that different modes of orienting can also influence the semantics of space.

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*Manuscript received November 2009*

*Manuscript accepted May 2010*

*First published online August 2010*