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Biases in Attentional Orientation and Magnitude Estimation Explain Crossover: Neglect is a Disorder of Both

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Abstract

Crossover refers to a pattern of performance on the line bisection test in which short lines are bisected on the side opposite the true center of long lines. Although most patients with spatial neglect demonstrate crossover, contemporary theories of neglect cannot explain it. In contrast, we show that blending the psychophysical construct of magnitude estimation with neglect theory not only explains crossover, but also addresses a quantitative feature of neglect that is independent of spatial deficits. We report a prospective validation study of the orientation/estimation hypothesis of crossover. Forty subjects (17 patients with and without neglect following unilateral brain injury and 23 normal controls) completed four experiments that examined crossover using line bisection, line bisection with cueing, and reproducing line lengths from both memory and a standard. Replicating earlier findings, all except one subject group exhibited crossover on the standard line bisection test, all groups showed a spontaneous preference to orient attention to one end of the lines, and all groups overestimated the length of short lines and underestimated long lines. Biases in attentional orientation and magnitude estimation are exaggerated in patients with neglect. The truly novel finding of this study occurred when, after removing the line from the bisection task, the direction of crossover was completely reversed in all subject groups depending on where attention was oriented. These findings are consistent with our hypothesis of crossover: (1) crossover is a normal component of performance on line bisection; (2) crossover results from the interplay of biases in attentional orientation and magnitude estimation; and (3) attentional orientation predicts the direction of crossover, whereas a disorder of magnitude estimation, not previously emphasized in neglect, accounts for the quantitative changes in length estimation that make crossover more obvious in neglect subjects. Paradoxically, we observed that the traditional line bisection test is suboptimal for exploring crossover because lines elicit spontaneous orientation responses from subjects that confound experimental manipulations of attention. We

conclude that attentional orientation and magnitude estimation are necessary and sufficient to explain crossover and that bias in magnitude estimation is a core component of neglect.

INTRODUCTION

Overview

Neglect is a neurological disorder in which patients abnormally orient, respond, or attend to stimuli on the side of space opposite their brain injuries (Heilman, Watson, & Valenstein, 1985). Several theories have been developed to account for contralesional neglect, but none meet the challenge of explaining the crossover effect (crossover). In its simplest form, crossover refers to the fact that patients who show ipsilesionally displaced bisections on conventional line lengths (~20 cm) show contralesional bisections on shorter lines (~2 cm), the opposite of contralateral neglect.

Given this theoretical dilemma, many researchers have attempted to account for crossover in terms of experimental data or computational models that elaborate and extend established theories of neglect. All of these models assume that crossover is a pathological phenomenon tied to the clinical presence of neglect. However, we have recently demonstrated that this is not the case; crossover is a normal aspect of human performance on line bisection tasks. The challenge, therefore, is not to explain crossover as a component of the neglect syndrome per se, but rather to explain both crossover as a component of normal performance and its quantitative change after brain injury, leading to its most dramatic presence in cases of neglect.

In this article, we examine the validity of our hypothesis that attentional orientation determines the direction in which crossover occurs and that systematic bias in length estimation actually yields the crossover effect (Mennemeier, Vezey, Lamar, & Jewell, 2002). The hypothesis accounts for the performance of normal subjects, neglect subjects, and subjects with brain injury but without neglect. Predictions based on this hypothesis were tested in four experiments using subjects with and without brain injury and with and without neglect. Our article begins by briefly reviewing the history and characteristics of crossover in neglect. We then discuss “attentional orientation” and “magnitude estimation,” which form the two core components of our hypothesis. Next, we present the results of our experiments. We conclude with a general discussion of these ideas and offer a broader theoretical framework for spatial neglect, one that addresses the pervasive problem of judging stimulus intensity, of which length estimation is merely one example.

A Brief History of Crossover and its Relation to Neglect—Neglect has been observed to be more common, severe, and persistent after right brain injury (Halligan, Burn, Marshall, & Wade, 1992) and is most frequently associated with stroke (Chatterjee & Mennemeier, 1998; Stone, Wilson, & Wroot, 1991). The brain systems typically associated with neglect are the heteromodal association cortex and nuclei in the thalamus, the basal ganglia, and the brain stem (Karnath, Himmelbach, & Rorden, 2002; Karnath, Ferber, & Himmelbach, 2001; Heilman, Watson, & Valenstein, 1994; Rizzolatti & Berti, 1993; Vallar & Perani, 1987; Mesulam, 1981; Watson, Valenstein, & Heilman, 1981). One of the classic

bedside tests for the demonstration and assessment of neglect is to have patients mark the middle of horizontal lines drawn on a piece of paper (Schenkenberg, Bradford, & Ajax, 1980). Subjects with neglect will generally misbisect lines on the same side as their brain injury (i.e., contralateral neglect).

Bisiach, Bulgarelli, Sterzi, and Vallar (1983) observed that bisection error systematically increased with line length in subjects with neglect. Halligan and Marshall (1988) noted that if the same trend were to continue for progressively shorter lines, the neglect subjects' bisection marks would actually cross over to the opposite side. Marshall and Halligan (1989) and Halligan and Marshall tested and confirmed this surprising idea. Subsequent studies showed that crossover occurs in most patients with neglect from right hemisphere injury (Chatterjee, Dajani, & Gage, 1994; Tegner & Levander, 1991).

Crossover bisections on short lines present an immediate challenge to contemporary theories concerning spatial neglect (Anderson, 1996; Bisiach, Rusconi, Peretti, & Vallar, 1994). Attentional theories explain contralateral neglect as a failure to deploy attention contralateral to brain injury (Heilman et al., 1985; Heilman & Van Den Abell, 1980), an inability to inhibit attention ipsilateral to brain injury (Kinsbourne, 1970), or an inability to disengage attention ipsilaterally (Posner & Dehaene, 1994). Motor theories of neglect invoke a failure to initiate movements in the direction contralateral to brain injury (Watson, Valenstein, & Heilman, 1978). Representational theories propose an inability to construct contralateral mental representations of space as well as objects in space (Bisiach & Luzzatti, 1978). Space exploration theories assert that the field of exploration is deviated ipsilesionally, resulting in contralesional neglect (Karnath, Niemeier, & Dichgans, 1998). Crossover bisections on short lines are at odds with each of these theories because they give the appearance of ipsilesional rather than contralesional neglect.

Explaining Crossover—Five explanations of crossover per se and three relevant computational models of line bisection have been proposed. A critical review can be found in Monagan and Shillcock (1998). Table 1 provides a concise summary.

Two explanations of crossover emphasize bias in attentional orientation. Kinsbourne (1993) explains crossover solely in terms of attentional bias. He argues that patients with left neglect merely fixate as far left from the right end of a line as their rightward attentional bias will permit. They bisect the line at this point. Crossover results from undershooting the true center of long lines and overshooting the center short lines. Marshall and Halligan (1989) explain crossover as a contrast between abnormal performance on long lines and normal performance on short lines. They argue that the just noticeable difference between two segments of a bisected line increases disproportionately with the line's total length, creating a "zone of indifference" that is very large on long lines and negligible on short lines. Patients with left neglect approach the indifference zone from the right on long lines, owing to a strong contralateral bias of spatial attention, and bisect the line immediately upon reaching this zone. On short lines, however, patients are assumed to revert to a "normal" approach strategy from the left and to make small contralateral bisection errors (Bowers & Heilman, 1980).

Three explanations of crossover emphasize altered perceptions of line length. All of them assume, either implicitly or explicitly, that attention is oriented toward the right end of lines prior to bisection. Chatterjee (1995) and Tegner and Levander (1991) explain crossover as a contrast between errors of omission on long lines (neglect) and errors of commission on short lines (completion phenomena or confabulation). Tegner and Levander posited two independent mechanisms for the bisection of small and large objects: a “right pushing” mechanism for large objects (hyperattraction) and a “left pushing” mechanism for small objects (perceptual completion). Chatterjee and Chatterjee, Dajani, et al. (1994) proposed that bisection errors on long and short lines are different parts of the same process, which can be expressed mathematically by a power function that relates objective line length to perceived line length (Stevens, 1975; Stevens & Galanter, 1957) (vida infra). Crossover bisections on short lines result from decreased inhibition of leftward, confabulatory mental representations. Although confabulation is also assumed to occur on long lines, it is masked by a restricted window of attention located contralateral to brain injury. Finally, Marshall, Lazar, Krakauer, and Sharma (1998) explained misperceiving line length in terms of stimulus context effects that cause short lines to be perceived as longer and long lines to be perceived as shorter than their objective length (Cross, 1973; Hollingworth, 1909). Recently, Ishiai, Koyama, et al. (2004) proposed that mental representations of short lines are exaggerated in neglect due to stimulus context. Crossover stems from overestimating short lines and neglecting long lines.

Computational models of line bisection have emphasized altered gradients of attention across a horizontal axis of space in neglect. Anderson’s (1996) mathematical description of line bisection models crossover as a difference in attentional salience across a horizontal axis. The model is predicated on the hypothesis that the right hemisphere attends to both hemispatial fields and the left attends primarily to the right hemispatial field (Corbetta, Meizin, Shulman, & Peterson, 1993; Heilman & Van Den Abell, 1980). Crossover bisections are produced when the right hemisphere is “lesioned” in simulations. In contrast, Mozer, Halligan, and Marshall (1997) posit that crossover merely reflects a contrast between normally occurring, leftward attentional biases on short lines and abnormal, rightward biases on long lines. Their model has two components, a “retinal field” and an attentional mechanism that selects output from the retinal field. Lesioning connections between the left retinal field and the attentional mechanism can produce neglect on long lines but has little or no effect on short lines. Finally, Monaghan and Shillcock (1998) developed a computational model of line bisection that assumes symmetric, independent attentional processing in the two hemispheres, each of which possesses an attentional gradient favoring the contralateral hemifield. Their model produces crossover in its “damaged” state, following both right and left hemisphere lesions (RHL and LHL).

Although each explanation and model can account for crossover in neglect, they are all limited by being predicated on neglect. They do not predict crossover in normal subjects or in patients without neglect. Even the theories that assert that crossover bisections on short lines represent normal performance emphasize a contrast with abnormal performance (neglect) on long lines. However, crossover does occur normally and in subjects without neglect.

Crossover, Orientation Bias, and Magnitude Estimation—Crossover has been observed on line bisection and length estimation tasks in both young and old normal subjects (Mennemeier, Vezey, Lamar, et al., 2002; Mennemeier, Rapcsak, Pierce, & Vezey, 2001; McCourt & Jewell, 1999; Mennemeier, Rapcsak, Dillon, & Vezey, 1998; Manning, Halligan, & Marshall, 1990). Crossover also occurs in patients without neglect following right or left brain injury (Mennemeier, Vezey, Lamar, et al., 2002; Mennemeier, Rapcsak, Pierce, et al., 2001; Mennemeier, Rapcsak, Dillon, et al., 1998).

Crossover is not observed as consistently in normal subjects as it is in patients with brain injury. For example, Manning et al. (1990) only reported crossover in a subset of their normal sample. Rueckert, Deravanesian, Baboorian, Lacalamita, and Repplinger (2002) did not observe crossover in normal subjects when using a line bisection task, but did observe crossover using a modified Landmark Task, in which subjects detect asymmetries in prebisected lines (Milner, Brechmann, & Pasgliarini, 1992). The crossover effect is influenced by the sex and age of normal subjects. Pierce, Jewell, and Mennemeier (2003) found that normal male subjects, especially young men, produced reliable patterns of crossover, whereas women did not, regardless of age. Confounds due to sex of subject could have obscured crossover in the Rueckert et al. study, which included twice as many women as men. Thus, a comprehensive explanation of crossover will not only have to explain crossover in normal subjects, but will also allow for potential “spoilers” of the crossover effect.

Mennemeier, Vezey, Lamar, et al. (2002) proposed the orientation/estimation hypothesis of crossover as an alternative to existing explanations and models. Attentional orientation and magnitude estimation are independent cognitive operations that normally influence line bisection and which may be altered by brain damage. Attentional orientation is a concept fundamental to most theories of neglect that refers to a bias in the direction in which attention is oriented in space. Each cerebral hemisphere is presumed to orient attention toward contralateral space. The two hemispheres are also presumed to mutually inhibit each other but, in normal subjects, the inhibitory influence of the left hemisphere is stronger than that of the right (Kinsbourne, 1970), thus predicting that spatial attention should be biased toward the right in normal subjects. Subsequent research showed that eye movements were biased to the right when healthy subjects bisected 20-cm lines (shorter lines were not tested) (Ishia, Furukawa, & Tsukagoshi, 1989), consistent with the Kinsbourne hypothesis. Disinhibition of the left hemisphere, following right hemisphere damage, has been proposed to explain the extreme rightward bias of attention in patients with left neglect (Kinsbourne, 1970). The observation of right neglect following acute, left hemisphere damage (Halligan et al., 1992; Ogden, 1987) indicates that pronounced ipsilesional attentional bias can occur regardless of lesion laterality. Indeed, we confirmed rightward attentional biases on line bisection in patients with chronic right hemisphere stroke and leftward attentional biases in patients with chronic left hemisphere stroke (Mennemeier, Vezey, Lamar, et al., 2002). Our hypothesis of crossover proposes that attentional orientation is normally biased toward the right, secondary to the stronger influence of the left hemisphere. However, in patients with unilateral brain lesion, attentional orientation is biased ipsilateral to brain injury, secondary to the lesion-induced disinhibition of the intact hemisphere.

In contrast to attentional orientation, the concept of magnitude estimation is not featured in any theory concerning neglect. However, magnitude estimation is directly relevant to perception of many different types of stimulus intensities, including line length. Magnitude estimation is a technique based on the Psychophysical Power Law, which concerns diverse perceptual continua (e.g., length, loudness, weight, pain) (Stevens, 1975). The Power Law holds that perceived intensity is related to physical intensity by a power function, as expressed mathematically by the equation $\psi = K\phi^\beta$, where ψ refers to the perceived stimulus value, ϕ is the physical stimulus value, and the constant K and the exponent β are empirically derived. When both the independent and dependent variables are log-transformed and plotted in power function relationships, a straight line results whose slope is the exponent of the power relation. The exponent thus reflects the ratio of change in perceived intensity relative to the ratio of change in physical intensity. The constant is equivalent to the y-intercept of the regression line. Although most psychophysical studies view the constant as a “scaling factor” without further elaboration (Stevens, 1975), Chatterjee (1995) showed that the constant assumes considerable importance in neglect (Chatterjee, Dajani, et al., 1994; Chatterjee, Mennemeier, & Heilman, 1994). Subjects with neglect typically have decreased exponents and elevated constants relative to normal subjects (Mennemeier, Vezey, Lamar, et al., 2002; Chatterjee, Dajani, et al., 1994; Chatterjee, Mennemeier, & Heilman, 1994) as well as right brain-lesioned patients without neglect (Kavcic, Kennelly, Soukup, & Harrell, 1996). A decreased exponent and increased constant indicate, in part, that affected patients overestimate the length of the shortest lines and underestimate the length of the longest lines relative to normal subjects. In essence, the range of their magnitude estimates for intensity is restricted relative to normal subjects.

The orientation/estimation hypothesis explains crossover in all subject groups as follows: Once attention is oriented preferentially to one end of a line, underestimating the true length of long lines causes the bisection mark to fall short of center, whereas overestimating the true length of short lines causes the bisection mark to go past true center (Figure 1).

Predictions based on this hypothesis were tested in four, prospective experiments as follows: (1) the same groups of normal control subjects (NCS, $n = 23$), patients with and without neglect following chronic right hemisphere lesions (RHL+ and RHL-, n sizes = 4 and 7, respectively), and patients without neglect following chronic left hemisphere lesions (LHL, $n = 6$) were tested in each experiment to determine whether crossover stems from normally occurring biases in attentional orientation and magnitude estimation (see Table 2 for subject characteristics); (2) Experiment 1 examined performance on the standard line bisection test to determine if NCS crossover from left to right, as predicted by a rightward bias in attentional orientation, and if patients crossover in an ipsilateral-to-contralateral direction, as predicted by an ipsilateral bias in attentional orientation; (3) Experiments 2 and 3 used cueing techniques (with and without the line present, respectively) to determine if the direction of crossover is predicted by the direction in which attention is oriented prior to bisection; and (4) Experiment 4 used a direct method of magnitude estimation, line length reproduction, to test predictions about group differences in magnitude estimation ability, specifically if magnitude estimation is altered in patients with neglect relative to either NCS

or patients without neglect. The same 10 line lengths (0.5, 1, 2, 5, 10, 20, 25, 30, 35, and 40 cm) were used in all experiments to facilitate comparison among experiments.

RESULTS

Experiment 1: Standard Line Bisection

The standard line bisection test was used to establish a “baseline” performance for each group and to test predictions that (1) NCS will crossover from right to left and patients will crossover in an ipsilateral-to-contralateral direction, (2) both NCS and patients without neglect will demonstrate crossover but RHL+ patients will have lower power function exponents and elevated constants relative to other subject groups.

Results—Bisection errors (and length reproduction in Experiment 4) were expressed as a percentage of the lines total length and z -transformed to facilitate comparisons among groups. A negative value was assigned to errors left of true center (or overestimates of length in Experiment 4) and a positive value was assigned to errors right of center (or underestimates of length in Experiment 4). Graphs of the z -transformed, signed percent error in Figure 2 illustrate the crossover effect for NCS, LHL, and RHL+ subjects. On average, both the NCS and RHL+ groups erred right of center on lines greater than 5 cm in length and to the left of true center on lines less than 5 cm (i.e., right-to-left crossover). In contrast, the LHL group made errors left of center on lines greater than 10 cm in length and right of center on lines shorter than 10 cm (i.e., left-to-right crossover). The RHL– group tended to bisect lines slightly right of true center without a prominent crossover effect. Bar graphs in Figure 3 illustrate the directional consistency of line bisection errors (and length estimation in Experiment 4). Errors on short lines (0.5 and 1 cm) were consistent in all but the RHL– group. In contrast, only NCS failed to produce a significant directional bias on lines longer than 5 cm.

Estimated line length was derived from line bisection performance by doubling the distance from the attended end of the line to the bisection mark. The attended end is assumed to be the right end for NCS and RHL subjects and the left end for LHL subjects. The data were log-transformed and estimated length was regressed on physical line length. The data for all groups fit power functions as r^2 values ranged from .92 to .99 (see Table 3). The size of power function exponents was different across groups (see also Table 3). Exponents for RHL+ were significantly lower than those for the remaining groups ($p < .01$), which did not differ from one another. No significant group differences were found for the constant. Power function data were examined for effects due to sex of subject, in this and all remaining experiments, but none were found.

Discussion—A crossover effect was evident in all subject groups except the RHL– subjects. The direction of crossover was consistent with our attentional orientation bias postulate in all groups where crossover was found. Finally, RHL+ patients had significantly lower power function exponents than any other subject group, indicating a greater deficit in magnitude estimation. Contrary to expectations, crossover was not observed in the RHL– group because, although they misbisected long lines to the right, they did not bisect short lines left of center. Further, the crossover effect for the NCS lacked a consistent directional

bias on longer lines. Attentional orientation could be less biased in NCS and RHL– patients than in LHL and RHL+ patients, leading to less consistent performance. Estimating line length from line bisection has an inherent interpretive limitation because it must be assumed that subjects orient consistently to one end of the lines. This situation makes it difficult to know whether subjects, such as the RHL– group, fail to crossover either because they failed to orient attention consistently or because they failed to make systematic errors in length estimation. The following experiment used cues to direct attentional orientation prior to bisection.

Experiment 2: Attentional Cueing

Most methods of cueing attention prior to bisection have a similar influence on the bisection of long lines (short lines have not been examined systematically) (Jewell & McCourt, 2000; Mennemeier, Vezey, Chatterjee, Rapcsak, & Heilman, 1997; Riddoch & Humphreys, 1983; Heilman & Valenstein, 1979). Cues draw the bisection mark toward the cued end of the line relative to no cues. Subjects were cued to one end of the line in this experiment by placing their pencil at one end prior to bisection (Mennemeier, Vezey, Chatterjee, et al., 1997). Estimated line length was calculated from the cued end of the line. Cueing NCS and RHL patients to the right end of the lines was predicted to either enhance crossover relative to no cues (Experiment 1) or not alter the crossover effect, whereas cueing the left was predicted to either disrupt or reverse the direction of crossover. The opposite result was predicted for LHL patients.

Results—A right cue enhanced the right-to-left crossover effect observed for NCS in Experiment 1 (Figure 2) as there was greater consistency in the direction of line bisection errors on lines longer than 5 cm (Figure 3). In contrast, a left cue diminished the crossover effect relative to no cues, and it disrupted the consistency of line bisection errors on the 1- and 2-cm lines.

For RHL+ patients, a right cue did little to alter the right-to-left crossover effect observed in Experiment 1, but right cues yielded greater consistency in the direction of line bisection errors, particularly on lines greater than 5 cm in length. In contrast, a left cue attenuated crossover relative to Experiment 1 as left cues were associated with less consistency on lines greater than 5 cm. Similarly, for LHL patients, a left cue did not alter the left-to-right crossover effect relative to Experiment 1 as the consistency of line bisection errors was approximately the same. However, a right cue disrupted this effect, leading to inconsistent bisection errors on all line lengths. Finally, for the RHL– patients, a right cue appeared to facilitate a right-to-left crossover effect relative to Experiment 1, but there was no consistency in the direction of these errors for any line length. Left cues were associated with leftward bisection errors relative to Experiment 1 but the direction of these errors was only consistent on lines greater than 20 cm.

The length estimation data fit power functions for all conditions and groups as r^2 values ranged from .87 to .99 (Table 3). A significant group effect was observed on the power function exponent in the right cue condition. The exponent for the RHL+ group was significantly lower than that for the remaining groups ($p < .0005$), which did not differ from

one another. A significant group effect was also found for the constant in the right cue condition. The constant for the RHL+ group was significantly higher than the remaining groups ($p < .001$), which did not differ from one another.

A significant group effect was observed on the power function exponent for the left cue condition. Interestingly, the exponent for the RHL+ group was significantly *higher* than those for the remaining groups ($p < .001$), which did not differ from one another. The RHL+ group also had a significantly *lower* constant than the remaining groups ($p < .001$) and the RHL- group had a significantly lower constant than the LHL and NCS groups ($p < .04$). The LHL and NCS groups did not differ from one another.

Finding that a left cue *increased* the size of the exponent and *decreased* the size of the constant among RHL+ patients is counterintuitive and not consistent with the graphed results. The most likely explanation is the left cue was not effective in orienting RHL+ patients to the left end of the line, and the results were an artifact of the way that estimated line length is calculated (i.e., from the left end of the line assuming subjects anchor attention there in response to the cue). However, if left cues are ineffective with RHL+ patients, then the estimated line length is incorrect. Therefore, estimates of line length were recalculated, assuming a rightward rather than a leftward orientation, and power functions were fit to the recalculated estimates. Consistent with the graphed results, the recalculated exponent was lower than other subject groups and the constant was higher; therefore, RHL+ patients did not appear to anchor attention to the left end of the line in response to a left cue.

Discussion—Consistent with predictions, cueing NCS to the right end of the line and cueing patients to the ipsilesional end either enhanced or did not alter crossover relative to Experiment 1, whereas cueing them in the opposite direction, respectively, either disrupted or attenuated crossover. However, cueing did not reverse the direction of crossover for any group. Further, it seems likely that RHL+ patients did not orient attention to the left end of lines even after placing their pencil point on the left end. These findings indicate that lines may elicit attentional orientation responses that can either complement or compete with cues depending on their location. This outcome was expected given a previous cueing experiment (Mennemeier, Vezey, Chatterjee, et al, 1997) and so Experiment 3 was designed to examine attentional orientation after removing the line from the bisection task.

Experiment 3: Reproducing Line Lengths from Mental Images Held in Memory

The orientation/estimation hypothesis predicts that the direction of crossover will reverse when attention is oriented in opposite directions; however, if lines elicit orientation responses, then a true test of the orientation/estimation hypothesis can only be achieved by removing the line from the task. Although other studies of neglect have used such an approach (Ishiai, Koyama, et al., 2004; Bisiach, Pizzamiglio, Nico, & Antonucci, 1996; Bisiach, Rusconi, et al., 1994), a study of normal subjects by Werth and Poppel (1988) is of particular relevance to this experiment. Werth and Poppel examined bias in length estimation using a method that removed the line from the task while simultaneously controlling attentional orientation. Subjects reproduced the half-length of lines held in memory starting either from a right or left endpoint printed on a blank sheet of paper. The

half-length of short lines (2 cm) was consistently overestimated and the half-length of long lines (20 cm) was underestimated regardless of starting location. Although the crossover effect was unrecognized at the time of Werth and Poppel's study, their method is particularly well designed to examine how attentional orientation influences the direction of crossover without orienting influences due to the line; specifically, to determine if the direction of crossover can be reversed by orienting attention in opposite directions after the line is removed.

Results—Normal control subjects performed the right endpoint condition similar to the standard line bisection task, erring right of center on long lines and left of center on short lines (Figure 2). Similar to Experiment 1, they were again consistent on short but not long lines (Figure 3). In contrast to Experiment 1, NCS reversed the direction of crossover when starting from the left endpoint. They erred left of center on long lines and right of center on short lines. The direction of errors was consistent on lines shorter than 5 cm and longer than 10 cm.

The same pattern of crossover was observed in all patient groups. When starting from the right endpoint, all patient groups erred to the right of center on long lines and to the left of center on short lines. The consistency of line bisection errors for RHL+ and LHL patients was similar to Experiment 1. RHL– patients were consistent on lines less than 5 cm. When starting from the left end, all patient groups crossed over in the opposite direction. Both RHL+ and LHL patients were consistent when bisecting lines less than 1 cm and greater than 25 cm. In contrast to the right endpoint condition, RHL– patients were consistent on lines greater than 10 cm but not on shorter line lengths.

The length estimation data fit power functions for all conditions and groups as r^2 ranged from .86 to .98 ($p < .04$). A significant effect of group was observed for power function exponents in the right endpoint condition. Exponents for the RHL+ group were significantly lower than those for the remaining groups who did not differ from one another ($p < .001$). A significant group effect was also found for power function constants in the right endpoint condition. The RHL+ group had a significantly higher constant than the remaining groups ($p < .04$), who again did not differ from one another.

Similarly, in the left endpoint condition, a significant group effect was found for the power function exponent, where the exponent for the RHL+ group was significantly lower than those for the RHL– and the NCS group ($p > .001$). Additionally, the LHL group had a significantly lower exponent than the RHL– group ($p < .04$). No significant group effect was found for the power function constant in the left endpoint condition.

Discussion—Removing the line from the bisection test yielded validation for the two core components of the orientation estimation hypothesis of crossover. All subjects overestimated the half-length of short lines and underestimated that of long lines. Neglect was associated with exaggerated bias in magnitude estimation. Most dramatically, the direction of crossover was shown to depend entirely on the location of the orienting endpoint. All subject groups crossed over in the same direction depending on the endpoint, and all groups reversed the direction of crossover when orienting to the opposite endpoint. A limitation of the memory-

based bisection method, however, is that group differences in memory ability could have influenced length estimates. Therefore, Experiment 4 was designed to examine length estimation using a direct method of magnitude estimation that does not depend on memory.

Experiment 4: Length Reproduction

The length reproduction method from Tegner and Levander's (1991) study of neglect was used in Experiment 4 to examine group differences in magnitude estimation without potential confounds due to memory ability. Subjects in that study drew a vertical line to match the length of a horizontal line printed across the top of the page (as if drawing one side of a square). All subject groups were predicted to overdraw the length of short lines and underdraw the length of long lines. Exaggerated bias in magnitude estimation was predicted for patients with neglect.

Results—All subject groups overdrawed the length of short lines and underdrew long lines (Figure 2). NCS, RHL+ and RHL– patients were consistent in this pattern on both short and long lines (Figure 3). Left hemisphere lesion patients were very consistent in underdrawing long lines; however, their tendency to overdraw short lines failed to reach statistical significance.

The length estimation data fit power functions for all groups; r^2 values ranged from .88 to .99 (Table 3). A significant effect of group on the power function exponent was found. The RHL+ group had a significantly lower exponent than the remaining groups ($p < .04$). Additionally, the RHL– group had a significantly lower exponent than the NCS group ($p < .026$). A significant group effect for power function constants was also found. The RHL+ group had a significantly higher constant than the remaining groups ($p < .001$). The RHL– again had a significantly higher constant than the NCS group ($p < .02$).

Discussion—All subject groups showed the expected pattern of overestimating the length of short lines and underestimating long lines. Although bias in magnitude estimation was, in fact, significantly more pronounced in patients with neglect, RHL– patients also showed exaggerated bias relative to NCS, indicating that bias in magnitude estimation may not be specific to neglect.

GENERAL DISCUSSION

The purpose and main findings of each experiment can be summarized as follows: (1) Experiment 1 examined whether the crossover effect extends to normal subjects and patient without neglect. All subject groups except the RHL– group showed a crossover effect. Crossover was exaggerated in patients with neglect (Mennemeier, Vezey, Lamar, et al., 2002). (2) Experiments 2 and 3 examined how attentional orientation influences the consistency and direction of crossover. In Experiment 2, cueing NCS to the right and cueing patients to the ipsilateral end of lines either enhanced the consistency of the crossover effect or did not alter it; whereas cueing attention in the opposite direction disrupted crossover. Cues could not reverse the direction of crossover in any group, and left cues seemed ineffective at reorienting attention in RHL+ patients, suggesting that lines may anchor attentional orientation toward the right in normal subjects and ipsilesionally in patients. This

hypothesis was supported by the results of Experiment 3. After removing the line from the task, all subject groups crossed over in the same direction when oriented to the same starting endpoint and the direction of crossover could be reversed, in all groups, by reorienting attention to the opposite endpoint. Experiment 4 used a length reproduction task to focus on group differences in magnitude estimation ability. With the exception of LHL patients who were not consistent on long lines, all subject groups tended to underestimate the length of long lines and overestimate short lines. Estimation bias was significantly greater in patients with right hemisphere injury, and especially in patients with neglect.

These findings support three main points which are discussed below. First, the orientation/estimation hypothesis is a valid, two-component model of crossover with advantages over existing explanations and models. Second, many factors can influence “crossover” via their influence on attentional orientation and magnitude estimation; however, studies in this report uniquely reveal how the presence of a line anchors attentional orientation. Third, neglect involves a disorder of magnitude estimation, in addition to a disorder of spatial attention. We now turn to the first point and a summary of the orientation/estimation hypothesis.

Because most explanations for crossover assume, at least implicitly, that RHL+ patients orient to the right end of lines prior to bisection and many view crossover bisections on short lines as productive errors, one might reasonably ask if the orientation/estimation hypothesis has any clear advantage over existing explanations and models. We assert that the orientation/estimation hypothesis has three distinct advantages. First, it is comprehensive. Because the orientation/estimation hypothesis explains crossover in terms of normally occurring biases in attentional orientation and magnitude estimation, rather than deficits associated with neglect, it can account for crossover in both normal subjects and patients without neglect. No other explanation or model predicts crossover in normal subjects, and only Monaghan and Shillcock’s (1998) model allows for crossover in patients with both right and left hemisphere lesions. Second, the orientation/estimation hypothesis makes novel predictions. Because magnitude estimation and attentional orientation are viewed as dissociable components of the crossover effect, it was possible to predict that the direction of crossover could be reversed by reorienting attention in an opposite direction. No other explanation or model makes this prediction; in fact, none would allow for a reversed crossover effect because productive errors are explained as a consequence of disordered spatial attention. Third, the orientation/estimation hypothesis resolves theoretical dilemmas posed by crossover for theories of neglect. Because the orientation/estimation hypothesis does not view crossover as a consequence of neglect, there is no theoretical impasse. This is not to say, however, that the discovery of crossover has been meaningless to neglect theory or that crossover reveals nothing about neglect-specific behaviors, like perceptual completion and confabulation. On the contrary, understanding crossover is important because it opens the door to the construct of magnitude estimation and to a potential shift in the way theorists may think about the quantitative aspects of “spatial neglect.” We now turn to the second point, regarding factors that influence crossover.

We mentioned above that crossover is observed less consistently in normal subjects than in patients with neglect. This might be due either to experimental factors such as the type of

task (Rueckert et al., 2002) or nonexperimental factors such as the age or sex of subjects (Pierce et al., 2003), as such factors may influence attentional orientation and magnitude estimation. The truly novel finding of this study concerned the degree to which the physical presence of a line anchors attentional orientation. In fact, lines appeared to elicit orientation responses that were even more compelling than direct attempts at cueing attention. For example, RHL+ patients bisected lines in Experiment 2 as if they oriented to the right end even though they began the task by placing their pencil at the left end of the lines! The potency of the line's orienting effect for RHL+ patients was more clearly illustrated by removing the line from the task in Experiment 3. Then, cueing RHL+ patients to the left end of the line completely reversed the direction of their crossover effect relative to all previous experiments. The apparent competition for attention between lines and cues, also evident in all other subject groups, is consistent with findings of other studies of attentional cueing, which show that cues draw bisection marks toward the cued location but do not reverse the direction of bisection errors (Jewell & McCourt, 2000; Mennemeier, Vezey, Chatterjee, et al., 1997; Riddoch & Humphreys, 1983; Heilman & Valenstein, 1979). Paradoxically, this finding implies that lines as stimuli may be suboptimal for testing explanations and models of crossover. For example, the line bisection task had to be deconstructed in order to reverse the direction of crossover in Experiment 3.

Removing the line from the bisection task may have simply eliminated the need to disengage attention from one end, thereby allowing subjects to fully orient to the cued location (Posner & Dehaene 1994). Mark, Kooistra, and Heilman (1988) showed that erasing, rather than canceling, lines on a cancellation test improved target omissions in patients with neglect, perhaps because erasing the visual stimulus facilitated disengagement from it. However, the normal subjects in this study would not be expected to have the same degree of difficulty disengaging attention as patients with neglect. An alternative explanation considers that attention can be oriented in space with regard to several frames of reference, centered either on the viewer, object, scene, or environment (Robertson, 1995; Chatterjee, 1994; Mennemeier, Chatterjee, & Heilman, 1994; Colby, 1993; Farah, Brunn, Wong, & Carpenter, 1990). Orienting attention either spontaneously or physically toward a cued location might operate through a viewer-centered reference frame, whereas orienting attention to a line may operate through an object-centered frame. Conflicting information from different reference frames might simply modify each other's influence, consistent with the typical cueing effect in line bisection; however, removing the line may eliminate competition from the object centered frame, yielding control to the viewer-centered frame and allowing the direction of crossover to be fully reversed.

Whereas the "presence" of a line influences the direction of crossover by anchoring attention toward one end, the line's "length" elicits bias in magnitude estimation that actually yields the crossover effect. Crossover depends on the directional consistency of line bisection errors. Consistency parallels bisection accuracy. Accuracy varies with line length—short lines being overestimated and long lines underestimated. The point of crossover is also a point at which bisections are most accurate and, as a result, least consistently bisected to one side of true center (Mennemeier, Rapcsak, Dillon, et al., 1998). Replicating previous experiments (Mennemeier, Rapcsak, Pierce, et al., 2001; Mennemeier, Rapcsak, Dillon, et al., 1998), normal subjects in this study were least accurate when bisecting the shortest lines

and the direction of errors on short lines was very consistent. So too, with the brain-injured patients. Patients with LHL were less accurate and more directionally biased on short lines than on the long lines. Patients with neglect from RHL produced the most robust crossover effect because they were as inaccurate when bisecting long lines as they were when bisecting short lines. The fact that the direction of crossover could be reversed by controlling attentional orientation merely underscores the point that attentional orientation and magnitude estimation are dissociable components of the crossover effect. We now turn to the final and most theoretically important point that neglect involves a disorder of magnitude estimation.

Magnitude estimation addresses quantitative variation in neglect—how much of a stimulus is neglected—separate from spatial deficits. It also quantifies neglect across testing methods and sensory domains. Bisection, cancellation, and reproduction tests all require direct judgments of stimulus magnitude. Tests for extinction require simultaneous comparisons of stimulus magnitudes (Chatterjee, Thompson, & Ricci, 1998). Power functions applied to cancellation data show that the total number of cancellation targets predicts the number neglected (Chatterjee, Mennemeier, & Heilman, 1992b), regardless of the spatial location of neglected cancellation targets (Chatterjee, Mennemeier, & Heilman, 1992c), again suggesting that quantitative and spatial aspects of neglect are dissociable. Power functions account for extremely large portions of variance on all these tests in normal subjects and patients with neglect (Pierce et al., 2003; Mennemeier, Vezey, Lamar, et al., 2002; Chatterjee, 1995; Chatterjee, Dajani, et al., 1994; Chatterjee, Mennemeier, et al., 1994; Chatterjee, Mennemeier, & Heilman, 1992a, 1992b).

The quantitative errors made by patients with neglect appear to represent a true deficit in magnitude estimation because they are not merely restricted to estimates of length or to “spatial” stimuli. Similar biases in magnitude estimation are evident when patients with right hemisphere injury judge the intensity of a wide array of perceptual continua spanning the visual, auditory, proprioceptive, tactile, and gustatory sensory modalities (Mennemeier, Murphy, Kretzmer, Jewell, & Nunn, 2003). Although, as in this study, exaggerated biases in magnitude estimation is not specific to neglect, it is significantly more biased in RHL+ patients than any other subject group. (The same point can be made about bias in spatial attention, which is not specific to patients with neglect, only greatly exaggerated.) So, it is as necessary to account for bias in magnitude estimation in neglect as it is to account for bias in spatial attention.

Magnitude estimation may be linked to neglect via the heteromodal association brain systems that are commonly implicated in neglect. A review of data from lesion, imaging, and transcranial magnetic stimulation studies involving human and animal subjects (Walsh, 2003) provided converging evidence for a “magnitude system” located in the association cortex in the parietal lobe of the right hemisphere. It was mentioned earlier that this brain region is most consistently linked with spatial neglect. Heteromodal areas mediate advanced levels of sensory processing (Mesulam, 1998; Watson et al., 1981). A notable property of cortical neurons (Schiller, 1996) is they become increasingly multifunctional as one ascends to advanced levels of processing. The purpose of multifunctional neurons is to extend processing capacities; to improve upon earlier signal processing stages (Schiller, 1996;

Schiller, Logothetis, & Charles, 1990). A decreased power function exponent, which implies a restricted range of magnitude estimates, is the most reliable marker of altered magnitude estimation in patients with neglect (Mennemeier, Vezey, Lamar, et al., 2002; Chatterjee, 1995; Chatterjee, Dajani, et al., 1994). We speculate that the heteromodal association areas implicated in neglect normally serve to extend the range of magnitude estimates, to improve discrimination at both the high and low ends of the range. Damage to these areas may compromise this extended functional capacity. This negative symptom of brain injury may be the primary reason for a diminished power function exponent in neglect, but other factors might also contribute to a lower exponent.

Compensatory behaviors, positive signs of brain injury, may further restrict the range of magnitude estimates in patients with neglect. Poulton (1979, 1968) identified six types of “response bias” in magnitude estimation that can lower the size of the power function exponent. So far, contextual effects are the only form of response bias that has been examined in neglect (Ishiai, Koyama, et al., 2004; Ricci & Chatterjee, 2001; Marshall et al., 1998). Both Ishiai, Koyama, et al. (2004) and Marshall et al. (1998) explain crossover as due to exaggerated stimulus context effects in neglect. In contrast, Ricci and Chatterjee (2001) found that absolute line length influences line bisection performance more than stimulus context in neglect. We suspect that patients who have a restricted range of magnitude estimates due to brain injury may adopt compensatory behaviors that make them more susceptible than normal subjects to several types of response bias (e.g., contextual effects, response perseveration, and categorizing stimuli), all of which can further lower the size of the power function exponent.

In closing, our results indicate that the orientation/estimation hypothesis is a valid and comprehensive explanation of the crossover effect on line bisection. More importantly, they show that neglect performance cannot be understood entirely as a disorder of spatial attention. Understanding the quantitative aspects of neglect performance (how much of a stimulus is perceived) requires a broader theoretical framework that includes magnitude estimation.

METHODS

Pretest Measures

All subjects completed the Behavioral Inattention Test (BIT) (Wilson, Cockburn, & Halligan, 1987) and the Mini Mental Status Exam (MMSE) (Folstein, Folstein, & McHugh, 1975). A composite score below 129 on the BIT strongly suggests neglect. A score below 25 on the MMSE indicates compromised mental status. Handedness was assessed by self-report and visual fields were examined using a standard bedside confrontation examination. This study was approved by our university’s institutional review board for human research. All subjects gave informed consent prior to participation.

Subjects

Subjects were 17 patients with unilateral brain lesions due to stroke and 23 elderly NCS. The 11 patients with RHL were divided into two groups based on BIT scores. Four were

below the BIT cutoff score for neglect and seven were above the cutoff. Lesion location was verified using clinically obtained MRI or CT scans when available and mapped using Damasio and Damasio (1989) templates (see Table 2 for a summary of lesion locations). Neuroradiologic studies were available for all but one of the RHL patients and all but two of the LHL patients. Neuroradiologic reports were used to verify lesion location in the case of missing scans. All patients were tested at least 2 months poststroke onset to avoid the rapid changes in behavior that can be observed earlier in the course of recovery.

Gender composition was not significantly different across groups. Two of 4 RHL+ patients, 3 of 7 RHL− patients, 2 of 6 LHL patients, and 10 of 23 NCS were men. The four groups differed significantly on BIT composite scores [$F(3,37) = 24.49, p = .<001$]. The RHL+ ($M = 77$) performed significantly worse on the BIT than the RHL− ($M = 141; p < .0005$), the LHL group ($M = 141; p < .0005$), or the NCS ($M = 143; p < .0005$). The RHL−, LHL, and NCS groups did not differ significantly on BIT scores. No significant group differences were found for MMSE scores (RHL+, $M = 25.7$; RHL−, $M = 27.9$; LHL, $M = 26.0$; NCS, $M = 27.1$). Groups differed significantly on age [$F(3,34) = 4.443, p = .01$]. The RHL + group ($M = 57.3$ years) was significantly younger than the NCS ($M = 71.1; p < .0005$). No other significant group differences for age were found (RHL−, $M = 55.8$; LHL, $M = 63.0$). All subjects, in all groups, were right-handed by report. Two of the RHL− patients showed left visual field cuts. Both patients had lesions involving the temporal lobes. The remainder of subjects did not show visual field defects. Eight of 11 RHL patients demonstrated left hemiparesis and 5 of 6 LHL patients demonstrated right hemiparesis. All RHL patients and NCS used their dominant right hand to perform tests. Four LHL patients used their nondominant left hand to perform tests.

Experimental Procedures Common to All Experiments

Subjects participated in all experiments according to a counterbalanced schedule that controlled for order effects. All experiments were completed in one test session. No constraints were placed on subjects with regard to eye or head movements during any experiment. Subjects performed all tasks with either their dominant hand or the hand less affected by stroke to obtain best motor control. Test stimuli were presented one at a time to eliminate direct comparisons between stimuli. Test stimuli were aligned along the horizontal axis of space relative to the subject. The center of the stimulus was aligned with the subject's midsagittal plane. Stimuli were presented on a white tabletop (62×94 cm) to obscure any borders created by the edges of the stimulus page. The order of test stimuli within each experiment was randomized.

Stimuli and Procedures Specific to Each Experiment

Experiment 1—Subjects bisected lines of 10 different lengths (0.5, 1, 2, 5, 10, 20, 25, 30, 35, and 40 cm) using a pencil. Each line length was presented three times. Line stimuli were 1-mm horizontal black lines centered on sheets of white paper (27.9×43.2 cm). The viewing distance was 30 cm. Subjects were instructed to bisect the line by cutting it into two pieces of equal length.

Experiment 2—In the cued condition, subjects oriented to either the right end of lines (right cue condition) or to the left end (left cue condition) by placing their pencil point at the respective end of the line prior to bisection. After orienting, subjects were instructed to move their pencil directly to the perceived center. They were discouraged from moving across the entire line length and from reorienting to the noncued end of the line. If they attempted to do so, the trial was repeated. Subjects completed all of the trials of one cue condition before beginning the next cue condition. The order of cueing conditions was counterbalanced across subjects. The test stimuli were identical to those of Experiment 1. The viewing distance was 30 cm.

Experiment 3—As in previous experiments, subjects were presented with lines that they viewed for 10 sec. Lines were 1-mm wide, black, and drawn on sheets of white paper (27.9 × 43.2 cm). The viewing distance was 30 cm. After the line was removed, subjects were presented a piece of white paper the same size as the paper on which the original stimulus had been presented. An endpoint, a single vertical line 1 cm in length was printed on either the right or left half of the paper indicating the right or left end of the line, respectively. Subjects were instructed to place a mark where the midpoint of the line would be relative to the endpoint presented on the page. Subjects indicated the midpoint of 10 line lengths (0.5, 1, 2, 5, 10, 20, 25, 30, 35, and 40 cm) for each of the two memory conditions (right vs. left endpoint), which were counterbalanced for order of presentation. Each line length was presented three times for each of the two endpoint conditions.

Experiment 4—Subjects placed their pencil on the right end of a horizontal line printed across the top of the page. They were instructed to draw a vertical line to match the length of the horizontal line, as if drawing one side of a square. Each set of lines consisted of 10 lengths (0.5, 1, 2, 5, 10, 20, 25, 30, 35, and 40 cm). Each line length was presented 3 times. Lines were 1-mm wide, black, and drawn on sheets of white paper (47.5 × 61 cm). The viewing distance was 30 to 50 cm.

Analyses

The Binomial Test was used to examine consistency in the direction of line bisection errors (Experiments 1–3) and type of length reproduction errors (underestimation vs. overestimation: Experiment 4). For Experiments 1–3, leftward bisection errors were coded as 0 and rightward errors as 1. For Experiment 4, underestimates were coded as 0 and overestimates were coded as 1. Hypotheses concerning magnitude estimation were tested using the power function exponent and constants as summary variables. Perceived line length was derived from the line bisection data, in Experiments 1–3, by doubling the distance from the attended end of the line to the bisection mark (see Pierce et al., 2003; Mennemeier, Vezey, Lamar, et al., 2002; Chatterjee, 1995; Chatterjee, Dajani, et al., 1994; Chatterjee, Mennemier, & Heilman, 1994). The right end of the line is assumed to be the attended end among normal subjects and RHL patients, whereas the left end of the line is assumed to be the attended end among LHL patients. When subjects were cued to one end of lines prior to bisection, the cued end is assumed to be the attended end. Power function exponents and constants were obtained by regressing the log-transformed estimates of length on the log-transformed objective line length. As mentioned earlier, exponents are equivalent

to the slope of the regression equation for log-transformed data and constants are equal to the y-intercept. In Experiment 4, power function exponents and constants were obtained by regressing the log-transformed length of the lines reproduced by subjects against the log-transformed objective line length. Power function data for all experiments appear in Table 3.

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Figure 1.

According to the orientation estimation hypothesis of crossover, subjects accurately bisect an anchored mental representation of the line which lead to misplacement of the physical bisection mark. Solid lines represent the true line length. Dotted lines represent the mental representation or estimated length. Asterisk represents attentional orientation. If a subject orients attention to the right end of the line and overestimates its true length, the physical bisection mark falls left of true center (short line, top of figure). If the subject orients to the right and underestimates its true length, the physical bisection mark falls right of true center (long line, bottom of figure). Orienting to the opposite end of the lines would reverse the direction of bisection error on short and long lines.

Figure 2.

Line graphs of the z -transformed, signed percent error scores for each group in each condition. Data from NCS are illustrated by the solid line, RHL+ data are shown by the dash-dot line, RHL- data are shown by the dotted line, and LHL data shown by the dashed line (see labeled lines in graph for Experiment 1). The point of crossover is the intersection of the plotted line for each subject group and the white line in each graph (zero percent error line). These graphs demonstrate that: (1) all but the RHL- group show crossover in the standard bisection experiment and that LHL patients crossover in a direction opposite NCS

and RHL+ patients during standard bisection; (2) right cues in NCS and ipsilesional cues in patients either do not alter or enhance crossover, whereas left and contralesional cues, respectively, have the opposite effect; (3) all groups crossover in the same direction depending on the orienting endpoint when the line is removed from the task; (4) all subject groups underdraw the length of short lines and overdraw that of long lines.

Figure 3.

Bar graphs illustrating the percentage of line bisection errors falling right and left of true center for each subject group in each experimental condition except the production task which shows the percent of lines that were either overdrawn or underdrawn. The y-axis of each graph shows the individual line lengths. The x-axis is divided. The right half (0 to 100%) indicates the percent of bisections falling right of true center (or underdrawn in the production task). The left half (labeled 100% to 0, with a negative sign to indicate leftward errors) denotes the percent of bisections falling left of center (or overdrawn in the

production task). Dark bars indicate that lines were bisected significantly to one side of true center according to the Binomial Test ($p < .05$). Light bars denote the absence of a significant directional bias. Scanning across rows allows within-group comparisons, and scanning down columns allows between-group comparisons. Part A presents data for the bisection and cuing experiments. Part B concerns the line absent and production experiments.

Table 1**A Summary of Previous Explanations and Models of Crossover**

Author(s)	Hypothesis	Applicability
Halligan and Marshall (1988)	Crossover relates to confabulation. A fixed attentional boundary exists left of the true midpoint for lines of all length. Patients bisect the extent of lines lying to the right of the boundary. Short lines do not reach the boundary and their left extents are confabulated.	Left neglect
Marshall and Halligan (1989)	Crossover results from different approach strategies on long and short lines. The just noticeable difference between two segments of a bisected line increases disproportionately with the line's total length creating a zone of indifference that is very large on long lines and negligible on short lines. Patients with neglect are thought to approach this zone from the right on long lines and from the left on short lines and to bisect lines immediately upon reaching the indifference zone.	Left neglect
Tegner and Levander (1991)	Crossover relates to perceptual completion. Two independent mechanisms mediate bisection on small and large objects: a "right-pushing" mechanism for long lines, such as ipsilesion hyperattraction, and a "left-pushing" mechanism for small objects, such as perceptual completion.	Left neglect
Chatterjee (1995)	Crossover bisections relate to productive errors caused by a generalized lack of inhibition of leftward confabulatory mental representations in the context of a rightward constricted window of attention. Leftward confabulations are also operative on long lines but masked by the greater effect of left neglect resulting in errors of omission. Productive errors and errors of omission are parts of the same continuous, power function.	Left neglect
Kinsbourne (1993)	Crossover results from rightward orientation and overshooting the midpoint of the line. Patients fixate as far left, from the right end of a line, as their rightward attentional bias will permit and, lacking any awareness of the true extent, bisect lines at that point. They stop short of the midpoint on intermediate and long lines but move past the midpoint on short lines.	Left neglect
Marshall et al. (1998)	Crossover relates to exaggerated stimulus context effects in length estimation. Assumes attentional orientation to the right end of lines. Short lines are overestimated and long lines are underestimated secondary to a regression of the patient's mental representations of lines toward the average of all lines presented.	Left neglect
Mozer et al. (1997)	Leftward bisections on short lines are normal. Crossover reflects the contrast between normal performance on short lines and abnormal performance on long lines.	Left neglect
Anderson (1996)	Crossover results from differences in attentional "salience" along the horizontal axis, the point at which left and right halves of lines are judged to be equal, secondary to an asymmetric distribution of attentional resources of the two cerebral hemispheres. Impairing the right hemisphere's function results in crossover.	Left neglect
Monaghan and Shillcock (1998)	Crossover relates to confabulation secondary to disinhibition of the intact hemisphere. The model assumes symmetric hemispheric processing, equal contralateral gradients of attention, and lesion-induced "noise" reflecting neuronal loss.	Left and right neglect

Table 2

Relevant Patient Information

ID#	Group	Sex	BIT	MMSE	Age	VFD	Hemi	Lesion Location
7	RHL-⊙	F	131	26	58	-	+	
9	RHL-	M	146	29	29	+	+	T
11	RHL-	F	144	29	68	-	-	MCA/ACA watershed⊙
12	RHL-	F	142	26	68	-	+	bg, pons⊙
14	RHL-	F	139	27	48	-	+	FTP
16	RHL-	M	141	29	61	-	-	bg
17	RHL-	M	141	29	64	+	-	TO
8	RHL+	M	118	28	56	-	+	FP
10	RHL+	F	115	22	65	-	+	T
13	RHL+	F	63	23	55	-	+	FTP
15	RHL+	M	13	27	53	-	+	FTOP
22	LHL	M	141	26	54	-	+	bg⊙
23	LHL⊙	M	140	28	59	-	+	
24	LHL	F	146	28	81	-	+	F
25	LHL	F	140	26	74	-	-	bg, pons⊙
26	LHL	M	142	25	44	-	+	th, icap⊙
27	LHL	M	134	23	66	-	+	F

BIT = Behavioral Inattention Test; MMSE = Mini Mental Status Exam; VFD = visual field defect; Hemi = hemiparesis; ⊙ = lesion location based on radiology report only; ⊙ = lesion laterality based on clinical signs only; F = frontal lobe; T = temporal lobe; O = occipital lobe; P = parietal lobe; bg = basal ganglia; th = thalamus; ic = internal capsule.

Table 3

Power Function Parameters by Condition for Each Subject Group

Condition	Subject Groups									
	NCS		RHL+		RHL-		LHL		Group Effect	
	con(L) ^{exp}	R ²	con(L) ^{exp}	R ²	con(L) ^{exp}	R ²	con(L) ^{exp}	R ²	exp	con
Line bisection	1.06(L) ^{0.98}	.998	1.13(L) ^{0.83}	.927	1.04(L) ^{1.0}	.998	1.1(L) ^{0.96}	.995	F(3,37) = 4.72 ****	F(3,37) = 1.05 *
Right cue	1.04(L) ^{0.98}	.997	1.21(L) ^{0.81}	.874	1.02(L) ^{1.0}	.987	0.99(L) ^{1.01}	.996	F(3,37) = 8.30 *****	F(3,37) = 4.97 ****
Left cue	1.03(L) ^{0.99}	.998	0.83(L) ^{1.09}	.993	.96(L) ^{1.0}	.994	1.07(L) ^{0.94}	.998	F(3,37) = 10.81 *****	F(3,37) = 10.72 *****
Right start	1.29(L) ^{0.91}	.982	1.86(L) ^{0.69}	.868	1.19(L) ^{0.91}	.966	1.36(L) ^{0.87}	.949	F(3,37) = 7.3 ****	F(3,37) = 3.2 **
Left start	1.18(L) ^{0.93}	.983	1.35(L) ^{0.79}	.875	0.98(L) ^{0.95}	.965	1.36(L) ^{0.87}	.952	F(3,37) = 5.16 *****	F(3,37) = 1.23 *
Line production	1.02(L) ^{0.99}	.993	1.48(L) ^{0.84}	.885	1.19(L) ^{0.91}	.993	1.08(L) ^{0.93}	.992	F(3,37) = 6.82 ****	F(3,37) = 9.28 *****

Con = constant; Exp = exponent; L = Length.

* $p > .05$.

**

$p < .05$.

$p < .01$.

$p < .001$.