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Crossover by Line Length and Spatial Location

Mark Mennemeier^{*}, Steven Z. Rapcsak[†], Chris Pierce[‡], and Elsie Vezey[§]

^{*}Department of Physical Medicine and Rehabilitation, University of Alabama

[‡]Department of Psychology, University of Alabama

[†]Department of Neurology, University of Arizona

[§]Department of Psychology, University of Arizona

Abstract

It is well known that line length has a systematic influence on line bisection error in neglect. Most patients with neglect misbisect long lines on the same side of true center as their brain lesion but then cross over on short lines, misbisecting them on the opposite side (i.e., crossover by line length). What is less recognized is that the spatial location of lines relative to the viewer can similarly induce a crossover effect when one considers line bisection error scores that have been averaged across individual line lengths. Patients with right hemisphere injury and neglect classically make averaged line bisection errors that fall right of true center on lines located either at midline or to the left of the viewer; however, we observed that the averaged line bisection error can fall left of true center when lines are located to the right of the viewer (i.e., crossover by spatial location). We hypothesized that crossover by both line length and spatial location stem from systematic errors in magnitude estimation, i.e., perceived line length. We tested predictions based on this hypothesis by examining how the crossover effect by line length is altered by the spatial location of lines along a horizontal axis relative to the viewer. Participants included patients with unilateral lesions of the right and left cerebral hemispheres and age-appropriate normal subjects. All groups demonstrated a crossover effect by line length at the midline location but the effect was altered by placing lines to the right and left of the viewer. In particular, patients with right hemisphere injury and neglect crossed-over across a broader range of line lengths when the lines were located to the right of the viewer rather than at either midline or left of the viewer. It is proposed that mental representations of stimulus magnitude are altered in neglect, in addition to mental representations of space, and that traditional accounts of neglect can be enhanced by including the psychophysical concept of magnitude estimation.

Keywords

hemispace; neglect; line bisection; magnitude estimation; mental representation

INTRODUCTION

When normal subjects are asked to judge the length of a range of lines, they underestimate the longest lines and overestimate the shortest (Hollingworth, 1909; Werth & Poppel, 1988; Tegner & Levander, 1991). Estimates of line length correspond to a well-established psychophysical principle of magnitude estimation, a discipline concerning perception of stimulus intensity. Whenever a range of stimulus intensities are presented for judgment, lesser stimuli in the range are judged to be larger than the objective value, whereas greater stimuli are judged to be smaller (Hollingworth, 1909). The dominant explanation for this phenomenon concerns contextual effects (see Algom & Marks, 1990), a type of regression bias in perception that is due to sequential dependencies in judgment (Cross, 1970). The range of stimulus intensities presented to a subject create a context in which judgments are made. Given that in any stimulus series lesser stimuli will, on average, be preceded by greater stimuli and greater stimuli will be preceded by lesser stimuli, sequential dependencies in judgment cause the range of estimated values to shrink and become centered within the range of objective values.

Parallel phenomena are observed among patients with spatial neglect. Neglect is characterized by the failure to report, respond to, or act on portions of stimuli located contralateral to a focal brain lesion (Heilman, Watson, & Valenstein, 1985). Neglect is theoretically linked to deficits in spatial awareness, including deficits in sensory attention, motor intention, and mental representation (Heilman & VanDenable, 1980; Kinsbourne, 1970; Posner & Dehaene, 1994; Watson, Valenstein, & Heilman, 1978; Mesulam, 1981; Bisiach & Luzzatti, 1978). Patients with neglect also overestimate the length of short lines (e.g., 2 cm) and underestimate long lines (e.g., 20 cm) (Tegner & Levander, 1991; Mennemeier et al., 2001). When reading letter strings (both words and nonwords), they may misperceive short strings as longer than the objective length and long strings as shorter than the objective length (Chatterjee, 1995). Contextual effects have also been observed (Marshall et al., 1998) such that lines of identical length may be bisected differently depending on the context in which they are presented. The primary difference between patients with neglect and normal subjects seems to be that patient errors are exaggerated relative to normal subjects (Mennemeier et al., 1998, 2001).

Mennemeier et al. (1998) proposed that the seemingly paradoxical crossover effect in neglect can be explained by systematic errors in length estimation. Crossover describes a specific pattern of performance on the line bisection test. Whereas long lines are bisected toward the end of the line ipsilateral to brain injury, short lines are bisected toward the end contralateral to brain injury (Halligan & Marshall, 1988). Crossover is typically described in terms of the direction of line bisection error on long-to-short lines, such as a right-to-left crossover effect among patients with right hemisphere injury and neglect.

Most explanations of the crossover effect propose a pathological mechanism related specifically to neglect (Chatterjee, 1995; Anderson, 1996; Kinsbourne, 1993; Marshall & Halligan, 1989; Tegner & Levander, 1991; Marshall et al., 1998). In contrast, Mennemeier et al. (1998, 2001) attribute crossover to two independent factors that normally influence bisection performance but are exaggerated in neglect—bias in attentional orientation and

systematic errors in magnitude estimation (i.e., the orientation/estimation hypothesis of crossover). Both normal subjects and patients with neglect are presumed to construct mental representations of lines and to anchor attention preferentially toward one end of the mental representation. If the mental representation is an underestimate of the true line length, as predicted for long lines, then the physical bisection mark will fall short of true center. However, if the mental representation is an overestimate, as for short lines, the bisection mark will go past true center, resulting in a crossover effect. The direction in which attention is anchored to lines predicts the direction in which crossover occurs. For example, patients with right hemisphere injury are expected to anchor attention toward the right end of lines, contralateral to their intact cerebral hemisphere, resulting in a right-to-left crossover effect, whereas the opposite pattern is expected among patients with left hemisphere injury. So far, the orientation/estimation hypothesis has received validation from studies showing that (1) crossover occurs among normal subjects as well as patients with neglect (Mennemeier et al., 1998, 2001; Manning et al., 1990), (2) a close correspondence exists between the direction of line bisection error and its estimated line length (Mennemeier et al., in press), and (3) crossover occurs in opposite directions between patients with unilateral left and right hemisphere injury (Mennemeier et al., in press). These studies indicate that line bisection involves cognitive operations related not only to spatial attention and spatial representation but also to psychophysical processes concerning magnitude estimation, each of which may be altered by brain damage.

While the crossover effect is traditionally conceptualized as an effect of line length on the direction of bisection error, Mennemeier et al. (1997) observed that line bisection errors can also be reversed across a horizontal axis of space. This observation raised the possibility that crossover can occur by spatial location. Patients with right hemisphere lesions and neglect bisected standard length lines (between 20 and 30 cm) at three spatial locations relative to the viewer—30 cm left of midline (left space), midline, and 30 cm right of midline (right space).

Whereas lines located at midline and in left space were bisected, as expected, on the ipsilateral side of true center, lines located in right space were bisected on the contralateral side of true center. Thus, crossover might occur across a range of spatial locations similar to the way that it occurs across a range of line lengths. Interestingly, earlier studies of normal subjects have shown a similar reversal of line bisection error occurs across a horizontal axis in space (Nichelli, Rinaldi, & Cubelli, 1989; Milner, Brechmann, & Pasglierini, 1992) and that size estimates may change across a horizontal axis of space. Both normal subjects and patients with unilateral brain injury tend to underestimate the size of stimuli located to the left of the body midline and to overestimate stimuli located to the right of the body midline (Gainotti & Tiacci, 1971; Milner et al., 1993; Nichelli et al., 1989).

Given the influence of spatial location on size estimation, we conjectured that the contralateral line bisection errors in right space, observed among right hemisphere lesioned patients, may constitute one piece of a crossover effect by line length that was altered by the spatial location of lines. Specifically, crossover may occur across a broader range of line lengths in right than left space because the line lengths are overestimated, generally, in right space and underestimated in left space. If so, these subjects should eventually make

ipsilateral line bisection errors in right space when given longer lines to bisect. Alternatively, their error scores might be reversed across space because they anchor attention to opposite ends of lines in left and right space. If so, administering longer lines in right space should not lead to ipsilateral bisection errors. Two experiments were conducted to test these predictions. The first attempted to replicate the earlier finding of contralateral line bisection errors in right space among patients with neglect because it is not commonly reported. The second tested whether these patients would demonstrate crossover across a broader range of line lengths in right space than either in left space or at midline. Patients with left hemisphere lesions and normal subjects were included as controls.

METHODS

Subjects

Twenty patients with unilateral right hemisphere lesions, 9 patients with unilateral left hemisphere lesions, and 11 age-appropriate normal control subjects participated. Mean ages were 65 years ($SD = 12$) for right hemisphere lesioned patients, 66 ($SD = 11$) for left hemisphere lesioned patients, and 72 ($SD = 8$) for normal controls. Ninety-five percent of right hemisphere lesioned patients were right handed by report compared with 90% of left hemisphere lesioned patients and 100% of normal controls. All patients were tested at least 2 months post lesion onset. Average lesion chronicity was 14 months ($SD = 16$) for right and 15 months ($SD = 15$) for left hemisphere lesioned patients. Age, handedness, and lesion chronicity did not differ significantly among these groups. Less than 10% of patients in either group demonstrated visual field defects to bedside confrontation exam. Clinically obtained CT or MRI studies were available for 85% of right and 73% of left hemisphere lesioned patients. Neuroradiologic reports of CT or MRI studies were used in place of missing films to confirm lesion location. Seventy-five percent of right hemisphere lesions were due to ischemic infarction, 15% to hemorrhagic infarction, and 10% to tumors and their resection. Ninety-one percent of left hemisphere lesions were due to ischemic infarction and 9% to hemorrhagic infarction. The Damasio and Damasio (1989) templates were used to plot lesions when CT and MRI studies were available. These images have been published elsewhere (Mennemeier et al., 1997, 1998). This study was approved by the University's Institutional Review Board, and all participants gave informed consent prior to entry. Subjects in this study also participated in a series of prospective investigations of the neglect syndrome (see Mennemeier et al., 1997, 1998).

Apparatus and Procedures

Neglect screening—A short battery of tests provided a composite neglect symptomatology score for each subject group. This battery rated 10 areas of functioning, including alertness, body kinesis, mood, orientation to external stimulation, extinction, limb akinesia, and motor impersistence, and it included drawing, copy, and cancellation tests. Criterion-referenced ratings were made for each subtest, and the composite score was obtained by summing respective subscale scores. Both left hemisphere lesioned patients and normal control subjects obtained lower composite scores on the neglect symptomatology battery than right hemisphere lesioned patients [$F = 8(2, 28)$, $p < .001$] but they did not differ from each other.

EXPERIMENT I: REPLICATION EXPERIMENT

Subjects bisected lines that were 24.1, 26.1, 28, and 30.2 cm in length and 0.2 cm in thickness. Lines were presented individually on legal-sized paper (11" × 17"). They were placed in three positions with respect to the body's midsagittal plane: 40 cm left, 40 cm right, and at the body midline. Lines were placed parallel to the coronal plane and located 30 cm in front of the subject. Patients were instructed to bisect the line with a pencil using the ipsilesional hand. Normal subjects used their preferred right hand. Three stacks of stimuli were placed in front of the subjects at the beginning of the experiment corresponding to the three spatial locations. Line length was randomized within each stack. Subjects worked through an entire stack before switching to the next, and the order was counterbalanced among subjects. Twelve line bisections (three trials at each length) were completed in each placement condition.

Data Analysis

The purpose of this analysis was to determine if, on average, patients made ipsilateral errors in left space and contralateral errors in right space. Error direction was coded as negative if the mark fell left of true center and positive if right of center. Error magnitude was calculated by measuring from the subject's bisection mark to the true center and then dividing this distance by the total line length (i.e., the percentage error score). MANOVA for repeated measures with planned contrasts were used to examine changes in the signed percentage error score across spatial location for each group.

Results

Right hemisphere lesioned patients—There was a significant main effect of spatial location on the signed percentage error score, $F(2, 18) = 5.46, p < .014$. Planned contrasts revealed that error scores in both left space [mean = 2.92 cm, standard deviation (SD) = 1.05] and at midline (2.10, $SD = .70$) were greater than those in right space (−.99, $SD = .96$), $F(1, 19) = 4.71, p < .04$. Additionally, the mean error in left space and at midline was ipsilateral to brain injury, whereas the mean error in right space was contralateral.

Controls

There was a main effect of spatial location on the signed percentage error score for normal subjects $F(2, 9) = 7.11, p < .014$. Error scores in left space (−.09, $SD = .48$) were smaller than those at midline (.55, $SD = .36$) and in right space (.78, $SD = .51$), $F(1, 10) = 9.9, p < .01$. There was no effect of spatial location on the signed percentage error score in patients with left hemisphere lesions (left space: −.95, $SD = .29$; midline: −1.54, $SD = .59$; and right space: −.93, $SD = .50$).

Discussion

Experiment I replicated an earlier finding. Patients with right hemisphere lesions made ipsilateral line bisection errors in left space and at midline and contralateral errors in right space. This finding constitutes a crossover effect by spatial location. Just as error direction is influenced by line length in the traditional conceptualization of crossover (Halligan & Marshall, 1989), spatial location can induce a crossover effect when error scores are

averaged and compared across a horizontal axis of space. Further, the result may not be specific to right hemisphere injury or patients with neglect because normal subjects also showed a trend toward reversed line bisection errors across space. In the follow-up experiment, a broader range of line lengths was administered at each spatial location to determine whether spatial location alters line bisection error by influencing length estimation or attentional anchoring.

EXPERIMENT II: THE INFLUENCE OF SPATIAL LOCATION ON THE CROSSOVER EFFECT BY LINE LENGTH

The same subjects from Experiment I bisected lines that were .5, 1, 2, 5, 10, 30, 50, and 80 cm in length and 0.2 cm in thickness. Twenty-four line bisections (three trials at each length) were completed in each placement condition. The remaining procedures were consistent with those used in Experiment I.

Data Analysis

The purpose of this analysis was to determine if right hemisphere lesioned patients made ipsilateral line bisection errors on longer lines in right space. Therefore, the proportion of lines bisected to the left and right of true center was analyzed for each line length at each spatial location using the Binomial test. Additionally, the effect of spatial location on the signed percentage error score was examined as in Experiment I.

Results

Right hemisphere lesioned patients—At the midline location (Fig. 1, center graph, gray bars), lines less than or equal to 1 cm were bisected more often on the contralateral side of true center, whereas lines greater than or equal to 10 cm were bisected more often on the ipsilateral side of true center (i.e., the traditional right-to-left crossover effect by line length). A similar pattern was evident in left space (Fig. 1, top graph, gray bars). In right space (Fig. 1, bottom graph, gray bars), lines less than 5 cm were bisected more often on the contralateral side of center, but only the longest line (80 cm) was bisected more often on the ipsilateral side of center.

There was main effect of spatial location on the signed percentage error score similar to that in Experiment I: $F(2, 18) = 3.48, p < .05$. On average, error scores in left space ($2.73, SD = .71$) and at midline ($.40, SD = .59$) were ipsilateral to brain injury, whereas errors in right space were contralateral to brain injury ($-1.04, SD = .45$).

Controls—Normal subjects (Fig. 1, center graph, open bars) also demonstrated a traditional right-to-left crossover effect at the midline location. They bisected .5-cm lines more often to the left of true center, whereas 5- and 10-cm lines were bisected more often to the right. However, in left and right space (Fig. 1, top and bottom graphs, open bars), only the lines less than or equal to 1 cm were bisected more often to the left of true center. No directional bias was observed on any other line length. Further, there was no effect of spatial location on the signed error as in Experiment I (left space: $-.70, SD = .34$; midline: $-.22, SD = .25$; and right space: $-.02, SD = .29$).

Left hemisphere lesioned patients—Patients with left hemisphere lesions (Fig. 1, center graph, black bars) demonstrated crossover at the midline location in a direction opposite the other two groups (left to right). Lines less than or equal to 1 cm were bisected more often on the contralateral side of center (i.e., right of true center), whereas lines 30 cm and greater were bisected more frequently on the ipsilateral side (left of center). In left space (Fig. 1, top graph, black bar), a significant ipsilateral bias was evident on the 2- and 30-cm lines. In right space (Fig. 1, bottom graph, black bar), a significant contralateral bias was evident on the .5-, 1-, 5-, and 50-cm lines. Finally, there was a significant main effect of spatial location on the average signed percentage error score, $F(2, 7) = 8.05, p < .015$. Similar to patients with right hemisphere injury, the left hemisphere lesioned patients also made ipsilateral errors in left space ($-.95, SD = .38$) and contralateral errors in right space ($1.34, SD = .32$).

GENERAL DISCUSSION

Experiment I confirmed that patients with right hemisphere injury and neglect can reverse the direction of their line bisection errors across a horizontal axis of space. This finding constitutes crossover by spatial location among patients with neglect. However, the effect might only be an exaggeration of normally occurring phenomena. Normal subjects showed a similar trend toward reversed errors in Experiment I, and patients with left hemisphere injury reversed the direction of their averaged line bisection errors in Experiment II when a greater range of line lengths was presented.

We predicted, based on the orientation/estimation hypothesis (Mennemeier et al., 1998), that if spatial location influenced the direction of the averaged line bisection errors across space by altering perceptions of line length, then patients with right hemisphere injury should make ipsilateral errors in right space when given longer lines to bisect. Alternatively, patients might anchor attention to different ends of the lines in right and left space; in which case, administering longer lines in right space should not lead to ipsilateral bisection errors. Examining the error scores for individual line lengths, within each spatial location, suggested that spatial location altered perceptions of length rather than attentional anchoring. Patients with right hemisphere injury demonstrated a crossover effect across a broader range of line lengths (5 to 80 cm) in right space than in either left space or the midline location (1 to 10 cm). Additionally, a right-to-left crossover effect was observed in all spatial locations, suggesting that attention was anchored consistently to the same ends of all lines.

Spatial location also altered the crossover effect by line length among patients with left hemisphere injury and normal control subjects. However, the data are less clear as to whether location altered perceptions of line length. Both groups demonstrated a crossover effect at the midline location. Patients with left hemisphere injury crossed over from left to right and normal subjects crossed over from right to left. However, neither group demonstrated a clear crossover effect by line length in either left or right space. Patients with left hemisphere injury tended to bisect all lines on the ipsilateral side of true center in left space and on the contralateral side of center in right space. This finding can suggest either that attention was anchored to different ends of the lines in left and right space or that, in

general, all line lengths were underestimated in left space and overestimated in right space. Normal subjects behaved more similarly to patients with right than left hemisphere injury. Although they failed to demonstrate a significant bias on long lines in either right or left space, they bisected short lines to the left of true center in all spatial locations and tended to bisect long lines to the right of center in all locations. Therefore, the most parsimonious interpretation of the data in Experiment II is that spatial location altered perceptions of line length for all groups of subjects, but the effect is exaggerated among patients with right hemisphere injury and neglect.

A question then arises as to how a range of line lengths and a range of spatial locations relative to the viewer can both lead to a crossover effect on line bisection. As we suspect that crossover stems from systematic errors in magnitude estimation, we suggest that both the range of line lengths and spatial locations employed in this study had a systematic influence on perceptions of length which manifested as a crossover effect on line bisection. It is acknowledged, however, that the mechanism(s) by which line length and spatial location may alter perceptions of length are open to speculation. We mentioned above that the dominant explanation of how a range of physical line lengths (i.e., stimulus context) can systematically bias perception is that context leads to sequential dependencies in judgment that facilitate the overestimation of short lines and the underestimation of long lines (i.e., regression in magnitude judgment). But the mere presence of stimulus context effects does not reveal the underlying neural mechanism. One possibility is that context acts as a priming mechanism in perception. By virtue of having previously constructed a mental representation of a line, the subject may be primed, at a neural level, to either over- or underconstruct the next representation depending on whether the preceding line was of greater or lesser length. Alternatively, stimulus context might only augment a physiologic bias inherent to the neural systems that either construct mental representations or transmit sensory-neural impulses. Earlier studies have shown that when context effects are measured directly in normal subjects, they actually account for less than 1% of the variance associated with magnitude judgment (Cross, 1970). Therefore, it is unclear whether stimulus context can fully explain the systematic bias observed in length estimation. In addition, preliminary studies in our laboratory (Mennemeier et al., 2000) indicate that both normal subjects and patients with neglect continue to overestimate short lines and underestimate long lines even when making judgments in the absence of a larger stimulus context. This result supports the notion that mental representations of stimulus magnitude are inherently biased.

Regarding the influence of spatial location on perceptions of length, a number of studies now document that perceptions of size are distorted across a horizontal axis of space among patients with neglect (Gainotti & Tiacci, 1971; Milner et al., 1993; Halligan & Marshall, 1991; Bisiach et al., 1996; Chokron et al., 1997; Kerhoff, 2000). Though interpretations of the data are not uniform, they either suggest that object size is relatively overestimated in right space and underestimated in left space among patients with right hemisphere injury and neglect (Gainotti & Tiacci, 1971; Milner et al., 1993) or that subjective impressions of space are relatively compressed in right space and expanded in left space (Halligan & Marshall, 1991; Bisiach et al., 1996; Chokron et al., 1997). Exceptions are noted as well (Karnath et al., 1991; Kerhoff, 2000). Asymmetries in size estimation across a horizontal axis of space have been explained as being due to either an effect of focused attention on size perception

(Gainotti & Tiacci, 1971), as focused attention is thought to magnify size, or to unspecified perceptual factors that work to alter size estimates of objects and space (Milner et al., 1993; Halligan & Marshall, 1991; Bisiach et al., 1996). An alternative hypothesis (Mennemeier et al., 1998) is that two cerebral hemispheres might be specialized for different aspects of magnitude estimation. The right hemisphere may process the full range of stimulus intensities presented to a subject, whereas the left may only process lesser stimulus intensities. Line lengths might be overestimated in right space among patients with neglect because their intact left hemisphere tends to overestimate the length of intermediate and long lines located in its contralateral field. Conversely, size estimates might be underestimated in left space because the damaged right hemisphere fails to process either long or short lines adequately. It is important to note, however, that hemispheric asymmetries in spatial attention (Kinsbourne, 1970) can have similar effects on perceptions of size across space. The relatively stronger attentional focus of the left hemisphere might magnify perceptions of size in right space, whereas the weaker attentional focus of the right hemisphere might facilitate underestimation in left space. Further work is necessary to learn how attention modifies perceptions of stimulus magnitude.

We have argued that, based on the orientation/estimation hypothesis, the crossover effect by both line length and spatial location stem from systematic errors in magnitude estimation. However, this interpretation is not the traditional means of explaining either the effect of line length or spatial location on line bisection performance in neglect. One might reasonably ask if the current interpretation is advantageous or even necessary. Line bisection errors are traditionally conceptualized as stemming from lateralized deficits in spatial attention and attentional orientation (Heilman et al., 1987; Kinsbourne, 1970; Riddoch & Humphreys, 1983; Reuter-Lorenz, 1990), movement (Heilman & Valenstein, 1979), mental representation (Bisiach & Luzzatti, 1978), and spatial memory and exploration (Heilman et al., 1987) following unilateral brain injury. While we do not refute the validity of these accounts as they relate to contralateral neglect, we recognize that they are not likely to be the whole story. First, traditional accounts of neglect have difficulty explaining bisection errors that are *reversed* across line length and spatial location because they are predicated on concepts of contralateral spatial inattention and altered representations of contralateral space. In contrast, the orientation/estimation hypothesis can readily explain bisection errors that are reversed across a range of line lengths and spatial locations because it views these errors as stemming from biased mental representations of stimulus magnitude (i.e., perceived length) that may be orthogonal to representations of space. Second, previous explanations of the crossover effect have been predicated on pathologic cognitive processes and mechanisms in neglect. They do not explain crossover in normal subjects or brain-damaged patients without neglect. In contrast, the orientation/estimation hypothesis can explain crossover in normal subjects because it posits that normally occurring biases in magnitude estimation are only exaggerated among patients with neglect.

In conclusion, the main advantage of the orientation/estimation hypothesis, in our opinion, lies in the recognition that mental representations of stimulus magnitude not only exist but also that they are altered in neglect in addition to mental representations of space. Adding the psychophysical concept of magnitude estimation to traditional accounts of neglect that

are currently predicated on concepts of spatial attention and spatial representation can yield greater degrees of freedom with which to interpret neglect behavior. For example, the concept of bias in magnitude estimation has made it possible to explain line bisection errors that are reversed across a range of line lengths and spatial locations in patients with otherwise classic signs of contralateral spatial neglect.

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FIG. 1.

Bar graphs showing the proportion of trials in which lines were bisected left or right of true center for each line length. Each bar represents 100% of the responses for a given line length. The bar's position with respect to percentage values at the top of the graph indicates how often lines were bisected left or right of true center. A negative value refers to leftward bisections; a positive value refers to rightward bisections. Black bars refer to left hemisphere lesioned patients, gray bars refer to right hemisphere lesioned patients, and open bars refer

to normal controls. An asterisk denotes significance at the $p < .05$ level according to the Binomial Test.