Published in final edited form as:

Brain Cogn. 1998 August ; 37(3): 439–459. doi:10.1006/brcg.1998.1007.

A Search for the Optimal Stimulus

Mark Mennemeier*, Steven Z. Rapcsak†, Melissa Dillon*, and Elsie Vezey‡

*Department of Physical Medicine and Rehabilitation, University of Alabama, Birmingham, Alabama

†Department of Neurology, University of Arizona, Tucson, Arizona

‡Department of Psychology, University of Arizona, Tucson, Arizona

Abstract

How do stimulus size and item number relate to the magnitude and direction of error on center estimation and line cancellation tests? How might this relationship inform theories concerning spatial neglect? These questions were addressed by testing twenty patients with right hemisphere lesions, eleven with left hemisphere lesions and eleven normal control subjects on multiple versions of center estimation and line cancellation tests. Patients who made large errors on these tests also demonstrated an optimal or pivotal stimulus value, i.e., a particular size center estimation test or number of lines on cancellation that either minimized error magnitude relative to other size stimuli (optimal) or marked the boundary between normal and abnormal performance (pivotal). Patients with right hemisphere lesions made increasingly greater errors on the center estimation test as stimuli were both larger and smaller than the optimal value, whereas those with left hemisphere lesions made greater errors as stimuli were smaller than a pivotal value. In normal subjects, the direction of errors on center estimation stimuli shifted from the right of true center to the left as stimuli decreased in size (i.e., the crossover effect). Right hemisphere lesions exaggerated this effect, whereas left hemisphere lesions diminished and possibly reversed the direction of crossover. Error direction did not change as a function of stimulus value on cancellation tests. The demonstration of optimal and pivotal stimulus values indicates that performances on center estimation and cancellation tests in neglect are only relative to the stimuli used. In light of other studies, our findings indicate that patients with spatial neglect grossly overestimate the size of small stimuli and underestimate the size of large stimuli, that crossover represents an “apparent” shift in error direction that actually results from normally occurring errors in size perception, and that the left hemisphere is specialized for one aspect of size estimation, whereas the right performs dual roles.

INTRODUCTION

Center estimation and cancellation tasks are commonly used to assess spatial neglect, a condition characterized by the failure to report, respond, or act on portions of stimuli located on the side of space contralateral to a focal brain lesion (Heilman et al., 1985). Center

estimation requires subjects to find the midpoint of a line, circle, square, or rectangle. Cancellation requires subjects to cross out target stimuli distributed across a page.

Despite the simplicity of center estimation and cancellation tasks, the patterns of performance associated with them can be complex and confusing. For example, Halligan and Marshall (1992) administered a star cancellation test and a line bisection test, consisting of lines ranging in length from 1.8 to 18 cm, to six patients with unilateral right hemisphere damage. The number of omitted stars and the linear regression of transection displacement for all lines were used to classify performances as either *impaired* or *unimpaired*. Two patients were unimpaired on both tasks, two were impaired on both, and two demonstrated impairment on one task but not the other. The latter “dissociations” lead Halligan and Marshall (1992) to question whether left hemispatial neglect is a meaningful theoretical construct.

It has become increasingly apparent, however, that simple comparisons between center estimation and cancellation tasks are not in and of themselves very meaningful. The tests lack a common measurement and their respective cognitive demands may place different constraints on awareness in neglect (Chatterjee et al., 1992c). Most importantly, altering the stimulus characteristics of each task can have a profound effect on performance that may create artificial dissociations. For example, we tested a patient with a large cerebral infarction of the right hemisphere who omitted all items on the left half of a 64-line cancellation test, but who was reasonably accurate in estimating the center of the page. In contrast, when he completed a 16-line cancellation test on a larger sheet of paper, he cancelled all of the items but placed his center estimation mark well into the right lower quadrant, thereby reversing his earlier “dissociation.”

Both the direction and magnitude of error on center estimation tasks is known to vary with stimulus size and shape (Bisiach et al., 1983; Tegner & Levander, 1991). Crossover is a stable component of line bisection performance in left neglect (Chatterjee, 1995; Halligan & Marshall, 1989b, 1988; Marshall & Halligan, 1989; Tegner & Levander, 1991), wherein small lines (<2 cm) are bisected left of true center and long lines (>10 cm) right of center. If the lines are made into parallelograms, patients who bisected long lines right of true center shift their mark to the left depending on the vertical height of the figure and its right vertical extent in particular (Halligan & Marshall, 1991; Marshall & Halligan, 1991). Error size also changes as a function of stimulus size (Halligan & Marshall, 1989b, 1988; Tegner & Levander, 1991) such that patients with neglect make abnormally large errors on both “long” and “short” lines but on intermediate lines their performance may be close to normal. Chatterjee demonstrated that the relationship between error size and line length is systematic and well described by a power function (Chatterjee, 1995; Chatterjee et al., 1994a,b). Anderson (1996) reproduced the crossover effect using a mathematical model of line bisection and simulated right hemisphere lesions. The above-mentioned studies have largely focused on an explanation of crossover in patients with left neglect. Less attention has been paid to the fact that these findings also imply an optimal size stimulus for each patient with neglect—one that minimizes error relative to other stimulus sizes. In fact, stimuli close to the optimal size may fail to elicit errors characteristic of neglect, whereas those exceeding the optimal size may produce clinical evidence of neglect.

Performance on cancellation tasks also varies according to a variety of stimulus and task factors. Patients with left spatial neglect typically omit left-sided targets (Albert, 1973) and targets in the left lower quadrant in particular (Halligan & Marshall, 1989a). However, the *location* of omissions can change as a function of starting position (Robertson & North, 1993) and search strategy (Chatterjee et al., 1992b). The *number* of omissions can change as a function of demands on selective attention (Rapcsak et al., 1989), the presence and location of distracting stimuli (Kaplan et al., 1991), and the method of cancellation (Ishiai et al., 1990; Mark et al., 1988; Robertson & North, 1993). In addition, Chatterjee et al. (1992a,b,c) demonstrated a stimulus–response relationship on cancellation tests in neglect such that a greater proportion of target stimuli are omitted as the total number of cancellation items increases. Therefore, on a standard line cancellation task (Albert, 1973), the total number of lines is predictive of the number neglected. Like center estimation, there should also be a particular number of lines that fails to elicit target omissions. We refer to this number as “pivotal” because it marks the boundary between normal and abnormal performance. Given the influence of stimulus and task factors on both center estimation and cancellation performance, it follows that (1) dissociations between them are relative to the methods employed and (2) direct between-task comparisons are probably not interpretable because the optimal size center estimation stimulus or the pivotal number of items on cancellation are not known in advance and are likely to vary between subjects. While we recognize that the critical measurement for center estimation tests is the *size* of the stimulus and for cancellation tasks it is the *number* of items, hereforward we use the mathematical term *value* (e.g., *optimal stimulus value*) in reference to both the size of a center estimation stimulus and the number of lines on a cancellation test.

In contrast to the influences of stimulus characteristics on center estimation and cancellation performance, much less is known about the relative contributions of the left and right cerebral hemispheres to each task. Studies of neglect tend to rely on patients with right hemisphere lesions (RHL) because neglect is both more severe and lasting than that following left hemisphere lesions (LHL). Normal control subjects (NC) are relatively underrepresented in studies of neglect and patients with LHLs are rarely included (Ogden, 1987; Schenkenberg et al., 1980). The lack of appropriate comparison groups further clouds our understanding of spatial neglect because one can not fully interpret performance patterns of RHL patients. For instance, while the crossover effect appears to be a stable component of line bisection performance in neglect, it is currently uncertain whether this phenomenon is pathological (Chatterjee, 1995) or whether it is a normal component of line bisection performance (Manning et al., 1990). Additionally, the relationships between stimulus value and neglect error has been shown for RHL patients but it is uncertain whether the same relationships would hold true for patients with LHLs. Finally, with only one brain-lesioned group, it is not possible to distinguish contributions of the left and right hemispheres to center estimation and cancellation. For example, in a previous study (Mennemeier et al., 1997), we found that the intact right hemisphere contributes more to line bisection accuracy than the left but that the left strongly biases errors to one side of true center.

In this report we present two experiments investigating the effect of stimulus value on center estimation and cancellation performance. Experiment I tested the hypothesis that

performance on center estimation and cancellation tasks are relative to the stimulus values employed. Patients with RHLs were the subjects. We predicted that changing the physical size of center estimation stimuli would affect both the proportion of the stimulus neglected and the direction of error relative to true center. In contrast, changing the physical size of a cancellation task would not effect performance, but increasing the number of items to be cancelled would lead to an increase in the number of items omitted. Experiment II investigated the contributions of each cerebral hemisphere to center estimation and cancellation performance. Patients with LHLs and NC subjects were tested using the same methods as in experiment I. Specifically, we predicted that (1) LHL would be associated with smaller absolute error magnitude scores than RHLs and (2) that patients with LHLs would be less directionally biased than NC subjects, whereas patients with RHLs would be more strongly biased than NC subjects. Finally, we analyzed data for individual RHL and LHL patients to determine whether an optimal or pivotal stimulus value existed for each subject on each task.

EXPERIMENT I: INVESTIGATION OF THE EFFECTS OF STIMULUS SIZE ON CENTER ESTIMATION AND CANCELLATION PERFORMANCE IN PATIENTS WITH RIGHT HEMISPHERE LESIONS

Subjects

Twenty patients with unilateral right hemisphere lesions were investigated. Their mean age was 65 (SD 12) years. Ninety-five percent of the patients were right handed by report. All patients were tested at least 2 months post lesion onset. Average lesion chronicity was 14 (SD 16) months. Lesion location was confirmed by CT or MRI in 85% of cases (Fig. 1). Neuroradiologic reports were used in place of actual films for the remaining cases. Seventy-five percent had ischemic infarctions, 15% had hemorrhagic infarctions, and 10% had lesions secondary to tumor resection. All subjects participated in this experiment as part of a series of prospective experiments investigating the neglect syndrome (see also Mennemeier et al., 1997).

The current study was approved by the University's Review Panel for the use of Human Subjects in Research.

Methods

Stimuli, apparatus, and procedures—Center estimation tasks consisted of five, rectangular, sheets of paper or “planes.” Their sizes varied considerably and as follows: (a) 2.2 by 2.8 cms (6.16 sq cm), (b) 12.7 by 16.4 (208.28), (c) 27.9 by 43.2 (1205.28), (d) 63.0 by 81.5 (5134.50), and (e) 91 by 121.5 (11,056.50). Cancellation tasks were the same size as the letter a, c, and e planes. They contained either 32 or 64 lines distributed evenly among the four quadrants of the page. All test stimuli were placed on a large table angled approximately 25° to afford a full view. The center of the stimulus was aligned with the subject's mid sagittal plane and placed at a comfortable distance (from 30 to 50 cm from the subject). Subjects were required to place a pen tip in the “center” of the planes and to cross out “all lines” on cancellation tasks. Patients used the hand ipsilateral to the lesioned

hemisphere. Three trials were completed for each center estimation task (3 trials $\times$ 5 sizes = 15 total). Two trials were completed for each cancellation task (2 trials $\times$ 2 target numbers $\times$ 3 sizes = 12 total). The order of trials was counterbalanced and administered in blocks.

A short battery of neglect tests was also administered to provide a composite neglect symptomatology score for screening purposes. This battery rated 10 areas of functioning including alertness, body kinesis, mood, orientation to external stimulation, extinction, limb akinesia, and motor impersistence and includes drawing, copy, and cancellation tests. Criterion referenced ratings were made for each subtest. The composite score was obtained by summing respective subscale scores.

Analysis—Our hypotheses concerned continuous (error magnitude) and categorical variables (error direction). Error magnitude was denoted by a percentage error score (PES). The PES for center estimation tasks was determined by (1) measuring the distance between the patient's mark and the nearest horizontal and vertical side, (2) doubling and multiplying these distances to yield the area processed, (3) subtracting from the total area to yield the error, and then (4) dividing by the total area to yield the percentage of error relative to the whole stimulus. The PES for cancellation tasks was determined by (1) dividing the total area by the number of cancellation marks, (2) multiplying this number by the number of omitted items, and then (3) dividing by the total area. This calculation assigns each cancellation target an area value and expresses omissions as a percentage of the total area.

Error direction was evaluated with respect to biases in the horizontal and vertical directions. On center estimation, horizontal biases were coded as 0 if the subject's mark fell left of true center, 1 if it was right of center, and 2 if it fell on the center. Vertical biases were coded as 0 if it fell below true center, 1 if it was above center, and 2 if it fell on the center. On cancellation tasks, biases in the horizontal direction were determined by counting the absolute number of lines cancelled on the left and right halves of the page. Horizontal biases were coded as 0 if more items were cancelled on the left, 1 if more lines were cancelled on the right, and 2 if an equal number of lines were cancelled on both sides. Similarly, vertical biases were determined by counting the number of items cancelled in the lower and upper halves of the page. They were coded as 0 if more lines were cancelled in the lower half of the page, 1 if more were cancelled in the upper half, and 2 if the number of cancellations was equal.

Group differences in the PES were evaluated using a one-way ANOVA and the LSD multiple range test. Data were collapsed across stimulus size prior to this analysis. Effects of stimulus size and item number on the PES were evaluated using MANOVA for repeated measures with difference contrasts. Degrees of freedom were adjusted using Huynh-Feldt Epsilon whenever sphericity assumptions were violated (* denotes corrected *df*). Data were orthonormalized prior to the analysis of contrasts. Directional biases were examined using the binomial test, employing only those trials coded 0 or 1. Individual subject data were analyzed to determine the number of patients in each group who performed either normally or abnormally relative to controls. For this analysis, we compared their scores to the 95 and 99% confidence limits set by controls for each task. Finally, individual subject data were also analyzed to determine whether there was an optimal stimulus value for each subject.

This analysis is described in more detail below (see analysis of the PES in center estimation for individual subjects).

Results

Results for the PES in center estimation—Nineteen of twenty RHL patients obtained mean PES scores that exceeded the upper 95% confidence limit set by NC subjects (i.e., a PES of 7.27%). As a group, their PES changed as a function of plane size ($F = 3.41(2,24^*)$ $p < .05$) (Table 1). The PES became increasingly larger for plane sizes b–e; however, the PES for the smallest plane (size a) was actually larger than for the next two plane sizes (b and c). The differences between plane sizes a and b ($t = -2.13$, $p < .04$) and e and the rest ($t = 2.07$, $p < .05$) were significant.

Results for error direction in center estimation—Marks were placed on the true *horizontal* center in 24% of trials for plane size a and 8% of trials for plane size b but not in any of the other plane sizes. An examination of the marks placed left and right of true center revealed significant directional biases on 4/5 plane sizes (Table 2). Marks were placed significantly more often to left of true center on the smallest plane size (a) but right of center on plane sizes c thru e. Regarding the vertical dimension, marks were placed on the true vertical center in 39% of trials for plane size a but not on any other plane sizes. A significant directional bias was only observed on plane size b and this bias was above the true center.

Results for the PES in cancellation—Normal control subjects did not make errors on the 32-line test; however, their 95% confidence limits on the 64-line test were .14 and .71, respectively. Eighteen of twenty RHL patients obtained scores exceeding the upper limit for the 64-item test. As a group, their PES increased significantly with target number, i.e., 32 versus 64 items ($F = 13.5(1, 17)$ $p < .002$) (Table 1). As individuals, six subjects (30%) did not miss any items on the 32-line cancellation tasks but their performance on the 64-line test fell outside the upper 95% confidence limit for normal controls. The remaining subjects omitted more targets than NC subjects on both the 32- and 64-line tests.

Results for error direction in cancellation—Significantly more items were cancelled on the right than left side of the page ($p < .05$, binomial test) regardless of the size or number of items on the cancellation task (Table 3). More items were also cancelled on the top than the bottom half of the page on the small (a) and medium (c)-sized cancellation tasks.

EXPERIMENT II: A COMPARISON OF PATIENTS WITH RIGHT AND LEFT HEMISPHERE LESIONS AND NORMAL CONTROLS

Subjects

Eleven LHL patients and 11 NC subjects were recruited as per experiment I. The mean age was 66 years (SD 11) for LHL patients and 72 years (SD 8) for NC subjects. Ninety percent of LHL patients were right handed by report compared with 100% of NCs. All patients had unilateral brain lesions. Lesion location was confirmed by CT or MRI in 73% of LHL patients (Fig. 1). Ninety-one percent of the LHLs were due to ischemic infarction and 9% to hemorrhagic infarction. Average lesion chronicity was 15 months (SD 15).

Methods

The methods were identical to those in experiment I.

Results

Results for screening tests—Subject groups did not differ in age or handedness. Patient groups did not differ in lesion chronicity. Both LHL patients and NC subjects obtained lower composite scores on the neglect symptomatology battery than RHL patients ($F = 8(2, 28) p < .001$) but they did not differ from each other.

Results for the PES in center estimation—As a group, both the LHL patients and NC subjects had smaller PES scores than RHL patients ($F = 14.1(2, 41) p < .00001$) and they did not differ from each other (Table 1 and Fig. 2). Individually, 7 of 11 LHL patients obtained PES scores exceeding the 95% confidence limits set by NC subjects. However, in contrast to the RHL group, the PES scores of the LHL group did not change as a function of stimulus size.

Results for error direction in center estimation—Normal controls placed their mark on the true horizontal center in 46% of trials for plane size a, 15% for plane size b, and 6% for plane size c but not on the other plane sizes. Significant biases were observed to left of true center on plane size a and to the right of center on plane size e (Table 2). Patients with LHL placed their mark on the true horizontal center in 30% of trials for plane size a and in 12% for plane size b but not on any of the other planes. They evidenced a bias on only one plane size (b) and this bias was right of true center. Regarding the vertical dimension, NC subjects were biased above true center on plane sizes b and c. Patients with LHLs were not biased in the vertical dimension.

Results for the PES in cancellation—Unlike RHL patients, NC subjects did not make errors on the 32-line cancellation test; however, their mean score on the 64-line test differed significantly from 0 ($t = 3.33(10) p < .008$) (Table 1). As a group, the PES for LHL patients did not differ from NC subjects. Individually, three LHL patients (30%) did not miss any targets on the 32-line test but their performance on the 64-line test exceeded the upper 95% confidence limit of NC subjects.

Results for error direction in cancellation—In contrast to RHL patients, neither the NC subjects nor LHL patients demonstrated directional biases on the 64-line cancellation tests owing to a general lack of target omissions (Table 3).

ANALYSIS OF THE PES IN CENTER ESTIMATION FOR INDIVIDUAL SUBJECTS

An exploratory analysis of the center estimation data was performed to determine whether an optimal or pivotal stimulus value could be identified for each patient—one that either minimized the PES relative to other plane values (optimal) or one that marked a boundary between normal and abnormal performance (pivotal). A PES was calculated for the horizontal dimension of each plane and plotted for each subject. We focused on the

horizontal axis because crossover was only demonstrated in this dimension and because crossover appears to be related to the optimal stimulus value. Plots were classified according to a system of rules that considered both the shape of the plot and the magnitude of error relative to NC subjects. Subjects were included in the analyses if they had complete data sets and if one or more of their PES scores exceeded the upper 99% confidence limit set by normal controls for each plane size (i.e., 8.9% for plane size a, 6.6% for plane b, 9.3% for plane c, 10.2% for plane d, and 9.7% for plane e). Seventeen RHL patients and seven LHL patients met these criteria. There were essentially three plot types which were defined as follows: (1) *U-shaped* (the PES for both small and large planes exceed the upper 99% confidence limit set by NC subjects *and* exceeded the PES for at least one intermediate size plane), (2) *skewed* (PES for *either* the small *or* large plane exceeds the upper 99% confidence limit set by NC subjects *and* the PESs for the remaining plane sizes), and (3) *variable* (PES for intermediate size planes exceeds the upper 99% confidence limit set by NC subjects as frequently as the small and large planes.)

Results

Seven of the RHL patients (41%) had u-shaped plots (Fig. 3a). The optimal stimulus value varied across patients. Three were most accurate when estimating plane size b, one was most accurate on plane size c, and another was most accurate on plane size d. Two subjects appeared equally accurate on plane sizes b, c, and d. Four RHL patients had skewed plots (Figs. 3b and 3c). Two were least accurate on small planes and most accurate on large planes (positively skewed). The others were least accurate on large planes and most accurate on small planes (negatively skewed). Six RHL patients demonstrated a variable pattern in which no obvious systematic relationship between stimulus size and PES was observed (Fig. 3d). Overall, patients with a variable pattern tended to have smaller PESs than those with U-shaped or skewed patterns and on average the shape of their plots did not differ markedly from that of the upper 99% confidence limits of NC subjects.

None of the LHL patients had U-shaped plots. Five had skewed plots, four were positively skewed (Fig. 4a), and one was negatively skewed (not shown in the figure). Two LHL patients demonstrated a variable pattern (Fig. 4b).

GENERAL DISCUSSION

Perhaps everyone who has examined patients with spatial neglect has been perplexed by the fact that they can perform normally on some tasks but not others. The current experiments were conducted to shed light on this confusing situation. We found that such “dissociations” may be relative to the stimuli employed. Changing the physical size of a center estimation stimulus profoundly affected both the magnitude and the direction of error in patients with RHLs, whereas changing the number of items on cancellation tasks affected the number of items omitted but not the direction of error. Further, for most of these patients, there was an either optimal or pivotal stimulus value—one that either minimized error relative to other stimulus values or one that marked the boundary between normal and abnormal performance. Exceeding the optimal or pivotal value had a detrimental effect on performance by increasing error magnitude. Given these results, it is easier to understand apparent dissociations in patients with neglect. A patient might perform normally on some

tasks because its stimulus value is close to the optimal or pivotal value for that task, whereas they may perform poorly on others because the stimulus exceeds the optimal or pivotal value.

Experiment II attempted to shed light on the hemispheric contributions to center estimation and cancellation performance. We found that lesions of the right cerebral hemisphere had a profound effect on error magnitude and on one's ability to accommodate changes in stimulus value. Lesions of the left hemisphere did not have as profound an effect on error magnitude but the individual patients who evidenced large error scores also had difficulty accommodating changes in stimulus value. Stimulus value did not effect error magnitude in NC subjects. We also found that RHLs were associated with an exaggeration of the directional biases observed in NC subjects (i.e., a right-to-left crossover effect in center estimation). In contrast, these biases were diminished and possibly reversed in patients with LHLs. In the discussion that follows we examine the evidence for optimal and pivotal stimulus values, discuss the differences between patients with RHLs and LHLs, and then draw conclusions.

RHL Patients

A curvilinear relationship was found between stimulus size and error magnitude on the center estimation test. Error magnitude was greatest for the small and large stimuli and least for the intermediate-size stimuli. Examining the center estimation performance of individual subjects provided direct evidence for an optimal stimulus value in 41% of cases. Seven patients were most accurate when estimating the center of intermediate size planes and least accurate when estimating large and small planes. However, not all patients demonstrated the curvilinear relationship. Four demonstrated a pivotal stimulus value, i.e., they were most accurate when estimating either small or large planes and least accurate at the other end of the continuum, and six patients did not demonstrate a clear pattern. The failure of the latter subgroup to demonstrate an optimal or pivotal stimulus value may relate to the fact that, on average, their error scores were smaller than those who did. It is less clear whether the patients who demonstrated a pivotal stimulus value actually represent a distinct subgroup. Relatively few patients fell in this group and the patients with negatively skewed plots may have actually demonstrated a U-shaped function had smaller stimuli been used. A wider range of stimuli in future studies could provide greater resolution of the optimal or pivotal stimulus values. Regardless of this uncertainty, the curvilinear relationship demonstrated by the RHL group suggests that a majority of these subjects are deficient in estimating the size of either "small" or "large" or both "small and large" stimuli but their performance can approximate normal if the "critical" stimulus value is used. Of course, small and large are terms that must be defined empirically.

Performances on cancellation tests can also be "normal" or "abnormal" depending on the number of targets used. For the group of RHL patients, a greater proportion of targets were neglected as the total number increased. As individuals, six subjects cancelled all targets on a 32-line cancellation test but missed significantly more targets than NC subjects on a 64-line cancellation test. We were not able to demonstrate a pivotal stimulus value for more of the RHL patients owing to the limited number of cancellation tests employed (only 32 and

64 items); however, had we included cancellation tests with either 8 or 16 items it seems likely that all of the patients would eventually have performed within normal limits. Unlike center estimation, there was no change in the *location* of item omissions as the total number of items increased. Nor did changing the physical size of the cancellation test alter performance. Therefore, it is apparent that direct comparisons between center estimation and cancellation performance are not readily interpretable without an a priori consideration of the optimal or pivotal stimulus values. In addition, because it is likely that the two tasks constrain performance in different ways (Chatterjee et al., 1992c), between-task comparisons may have limited usefulness.

The crossover effect on center estimation stimuli corresponded closely with changes in error magnitude. The largest absolute error scores corresponded with the presence of significant directional biases, whereas the smallest errors corresponded with the absence of a directional bias. For example, small planes were bisected significantly more often to the left of true center and large planes were bisected more often to the right. These were also the plane sizes in which the largest error scores were observed. In contrast, intermediate size stimuli were bisected equally often on both sides of true center and these were the planes with the smallest PES. Further examination of the individual RHL patients who demonstrated an optimal stimulus value also revealed a close correspondence between the point of crossover and the smallest PES in five of seven patients. These data are consistent with earlier reports of the crossover effect (Halligan & Marshall, 1988; Marshall & Halligan, 1989; Tegner & Levander, 1991). However, while earlier reports focused on the shifts in error direction as stimulus size changed, we have focused on the changes in error magnitude because we suspect that they are more important for understanding spatial neglect and because they may actually cause the “apparent” shifts in error direction. We return to this issue in the *Conclusion*.

Group Comparisons

With regard to error magnitude, patients with RHLs performed worse on both center estimation and cancellation tests than either LHL patients or NC subjects. As a group, patients with LHLs were not appreciably different from NC subjects on any comparison involving the PES. In addition, their PESs did not change significantly as a function of changes in stimulus size for either center estimation or cancellation tests. It appears that patients with RHLs not only make larger errors than patients with LHLs and NC subjects but also that their errors are more influenced by fluctuations in stimulus size. This interpretation is confounded, however, by the fact that RHL evidenced more neglect symptomatology on the screening battery than LHL patients. Neglect severity could relate to the ability to accommodate changes in stimulus size.

When plotting the performances of individual RHL and LHL patients, we specifically chose those patients who evidenced large PESs on one or more of the plane sizes. Here some similarities became apparent. Whereas none of the LHL patients had U-shaped plots, five demonstrated skewed plots that were, for the most part, in a positive direction. We also found that 30% of LHL patients performed within normal limits on the 32-line cancellation test but were significantly worse than NC subjects on the 64-line test. Thus, a subset of LHL

patients also demonstrated a relationship between stimulus size and error magnitude but, like the RHL patients, they had larger error scores than those who did not. The difference between RHL and LHL patients was that the patients with LHLs were less able to accommodate decrements in the size of center estimation stimuli, while RHL patients failed to accommodate increments as well as decrements. Thus, the relationship between stimulus size and error magnitude is most pronounced in the patients who evidence clinical signs of spatial neglect, such as large error scores. In addition, the two cerebral hemispheres may serve different functions with regard to size estimation.

With regard to error direction, it was the LHL patients who were most different from RHL patients and NC subjects. Patients with RHLs and NC subjects were similar in that both demonstrated a right-to-left horizontal crossover as center estimation stimuli decreased in size and both groups demonstrated vertical directional biases above true center on the intermediate size planes. However, the directional biases of RHL patients were more pronounced than NC subjects. Patients with LHLs failed to demonstrate significant directional biases and, if anything, tended to crossover in an opposite horizontal direction. Therefore, crossover appears to be a normal phenomenon of center estimation that is more robust following RHLs and less robust following LHLs. Unilateral brain lesions might also constrain the direction of crossover.

Conclusions

What roles do the left and right cerebral hemispheres play in size estimation? Data from this study indicate that the role of the left hemisphere is more specialized, whereas the right performs dual functions. We know that the left hemisphere contributes to size estimation because LHLs are associated with an increase in error magnitude scores relative to NC subjects in at least a subset of LHL patients. The left hemisphere appears to play a specialized role because these subjects had more difficulty with small than large stimuli. In contrast, the majority of RHL patients made large errors on center estimation stimuli and had difficulty with both large and small stimuli. Not only does the right hemisphere appear to be more important in size estimation but it also performs a dual role, processing small and large stimuli. These findings challenge traditional dichotomies used to describe lateralized differences in visuospatial processing, such as “part-whole” and “focal-global” (Robertson & Lamb, 1991; Robertson & Delis, 1986), because the right hemisphere’s function appears to overlap with that of the left, whereas the left may be specialized for one function.

The right hemisphere also orients attention toward right and left hemispace (Corbetta et al., 1993; Heilman & VanDenable, 1980), whereas the left hemisphere orients attention primarily toward right hemispace (Kinsbourne, 1970). The two hemispheres are mutually inhibitory of each other but the orientation bias of the left hemisphere is normally stronger than that of the right (Kinsbourne, 1970), so when spontaneous directional biases are observed in normal individuals they are probably more influenced by the left than right hemisphere. These lateralized differences in attentional orientation provide a feasible account of the directional biases we observed in our LHL and RHL patients. Left hemisphere lesions diminished directional biases relative to NC subjects, whereas RHLs exaggerated them. Right hemisphere lesions not only leave the left hemisphere intact but

they may also release it from inhibition, which could lead to an exaggeration of the directional biases that we observed in NC subjects. Conversely, LHLs may release the intact right hemisphere from inhibition, resulting in directional biases that are either diminished or reversed relative to NCs. This interpretation has direct implications for the crossover effect.

We stated earlier that the effect of stimulus value on error magnitude is more important for our understanding of spatial neglect than the shifts in error direction per se (i.e., crossover). We have reached this conclusion because crossover may only represent an “apparent” shift in error direction that actually results from overestimating the size of small stimuli and underestimating the size of large stimuli. First, crossover is a normal phenomenon of center estimation (see also Manning et al., 1990) that is governed by normal psychophysical principles (Chatterjee, 1995; Chatterjee et al., 1994a,b; Marshall & Halligan, 1989) and merely constrained by unilateral brain injury (Chatterjee et al., 1994a). Second, normal subjects and patients with RHL demonstrate crossover in the same direction, whereas patients with LHLs show a diminished and possibly reversed crossover effect. This suggests that the direction of crossover may depend on one’s initial orientation to the stimulus. (Here orientation implies that attention is preferentially, but not exclusively, allocated to one end of a stimulus prior to center estimation). Normal subjects and patients with RHLs may orient attention more frequently to the right side of center estimation stimulus because of the strong contralateral orientation bias of their intact left hemisphere. In contrast, patients with LHLs may either orient equally often to both sides of the stimulus or they may demonstrate a bias toward the left side of the stimulus, contralateral to their intact right hemisphere. In support of this hypotheses, we have found that cuing a RHL patient with neglect to the left end of a line prior to bisection reversed the direction of crossover (Chatterjee et al., 1994b). In addition, both normal controls and patients with left neglect spend more time searching the right sides of lines during line bisection (Ishiai et al., 1989). In contrast, normal subjects initially fixate the upper left quadrant in search tasks that are similar to cancellation tests (Behrmann et al., 1997). These finding supports our contention that line bisection and cancellation make different demands on attentional processing. (To our knowledge, no studies have examined eye movements when short lines are bisected. Nor have patients with left hemisphere lesions been tested.)

Third, Werth and Poppel (1988) found that normal subjects overestimate the size of small lines (4 cm) and underestimate the size of long lines (20 cm) regardless of whether they are orienting to the left or right end. Tegner and Levander (1991) showed that RHL patients with neglect also overestimate the length of short lines (2.5 cm) and underestimate that of long lines (20 cm). Thus, when normal subjects bisect small lines they may actually overshoot the true center because they overestimate the line’s total length. When bisecting long lines they may undershoot the true center because they underestimate its length. If one orients to the right end of a short line and *overshoots* the true center their center estimation mark will fall to the left of true center. Conversely, if one orients to the right end of a long line and *undershoots* the center their mark will fall right of true center. This is, in fact, the classic crossover effect. A reversed crossover effect would be predicted in subjects who orient more frequently to the left end of a line. In cases of spatial neglect, the normal errors in size perception are more pronounced, resulting in a gross overestimation of “small”

stimuli and a gross underestimation of “large” stimuli. Lesion laterality may influence attentional orientation and the direction of crossover.

Our search for the optimal stimulus revealed a relationship between stimulus value and error magnitude that may have its roots in normal perceptual processing. This relationship has practical and theoretical implications for spatial neglect. Practically, it seems likely that performance on most of the classic tests for neglect, such as drawing and reading, will also vary according to the stimuli used (Chatterjee, 1995). This obviously complicates clinical and research evaluations where there is a desire to know the breadth and severity of spatial neglect. It also complicates comparisons between tasks because performance may depend on the stimulus size as much as the task. Theoretically, the optimal or pivotal stimulus value represents a point at which one’s perception of size and amount most closely resembles the real stimulus environment. We do not know what mechanism gives rise to an overestimation or underestimation of stimulus size in normal individuals but, in cases of spatial neglect, this mechanism appears to be grossly unregulated. What is unusual from traditional accounts of spatial neglect, is that perceptions of small stimuli may actually be overestimated (Chatterjee, 1995; Tegner & Levander, 1991), which constitutes a productive error. Therefore, the term neglect may appropriately describe performance on stimuli that are “larger” than optimal but for smaller stimuli the term inflation seems more accurate. The common deficit in both instances would appear to be a dysregulation of normal perceptual scaling mechanisms.

Acknowledgments

Supported by First Independent Research Support and Transition Award (FIRST) from the National Institute of Neurological Disorders and Stroke No. 1R29NS31815; partial support was also provided by the University of Arizona McDonnell-Pew Cognitive Neuroscience Center and the Veterans Administration Hospital, Tucson Arizona.

References

- Albert ML. A simple test of visual neglect. *Neurology*. 1973; 23:658–664. [PubMed: 4736313]
- Anderson B. A mathematical model of line bisection behaviour in neglect. *Brain*. 1996; 119:841–850. [PubMed: 8673496]
- Behrmann M, Watt S, Black SE, Barton JJS. Impaired visual search in patients with unilateral neglect: An oculographic analysis. *Neuropsychologia*. 1997; 35:1445–1458. [PubMed: 9352522]
- Bisiach E, Bulgarelli C, Sterzi R, Vallar G. Line bisection and cognitive plasticity of unilateral neglect of space. *Brain and Cognition*. 1983; 2:32–38. [PubMed: 6546011]
- Chatterjee A. Cross-over, completion and confabulation in unilateral spatial neglect. *Brain*. 1995; 118:455–465. [PubMed: 7735886]
- Chatterjee A, Mennemeier M, Heilman KM. A stimulus-response relationship in unilateral neglect: the power function. *Neuropsychologia*. 1992a; 30:1101–1108. [PubMed: 1484604]
- Chatterjee A, Mennemeier M, Heilman KM. Search patterns and neglect: a case study. *Neuropsychologia*. 1992b; 30:657–672. [PubMed: 1528413]
- Chatterjee A, Mennemeier M, Heilman KM. A comparison of line bisection and cancellation in unilateral neglect. *Journal of Clinical and Experimental Neuropsychology*. 1992c; 14:85.
- Chatterjee A, Dajani BM, Gage RJ. Psychophysical constraints on behavior in unilateral spatial neglect. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology*. 1994a; 7:267–274.
- Chatterjee A, Mennemeier M, Heilman KM. The psychophysical power law and unilateral spatial neglect. *Brain and Cognition*. 1994b; 25:92–107. [PubMed: 8043269]

- Corbetta M, Meizin FM, Shulman GL, Peterson SE. A PET study of visuospatial attention. *Journal of Neuroscience*. 1993; 13:1202–1226. [PubMed: 8441008]
- Halligan PW, Marshall JC. How long is a piece of string? A study of line bisection in a case of visual neglect. *Cortex*. 1988; 24:321–328. [PubMed: 3416614]
- Halligan PW, Marshall JC. Is neglect (only) lateral? A quadrant analysis of line cancellation. *Journal of Clinical and Experimental Neuropsychology*. 1989a; 11:793–798. [PubMed: 2592524]
- Halligan PW, Marshall JC. Line bisection in visuo-spatial neglect: Disproof of a conjecture. *Cortex*. 1989b; 25:517–521. [PubMed: 2805738]
- Halligan PW, Marshall JC. Figural modulation of visuo-spatial neglect: A case study. *Neuropsychologia*. 1991; 29:619–628. [PubMed: 1944865]
- Halligan PW, Marshall JC. Left visuo-spatial neglect: a meaningless entity. *Cortex*. 1992; 28:525–535. [PubMed: 1478083]
- Heilman, KM.; Watson, RT.; Valenstein, E. Neglect and related disorders. In: Heilman, KM.; Valenstein, E., editors. *Clinical neuropsychology*. New York: Oxford Univ. Press; 1985. p. 243-293.
- Heilman KM, VanDenable T. Right hemisphere dominance for attention: The mechanism underlying hemispheric asymmetries of inattention. *Neurology*. 1980; 30:327–330. [PubMed: 7189037]
- Ishiai S, Furukawa T, Tsukagoshi H. Visuospatial processes of line bisection and the mechanisms underlying unilateral spatial neglect. *Brain*. 1989; 112:1485–1502. [PubMed: 2597992]
- Ishiai S, Sugishita M, Odajima N, Yaginuma M, Gono S, Kamaya T. Improvement of unilateral spatial neglect with numbering. *Neurology*. 1990; 40:1395–1398. [PubMed: 2392225]
- Kaplan RF, Verfaellie M, Meadows ME, Caplan LR, Pessin MS, Dewitt D. Changing attentional demands in left hemispatial neglect. *Archives of Neurology*. 1991; 48:1263–1266. [PubMed: 1845031]
- Kinsbourne M. The cerebral basis of lateral asymmetries in attention. *Acta Psychologica*. 1970; 33:193–201. [PubMed: 5445964]
- Manning L, Halligan PW, Marshall JC. Individual variation in line bisection: A study of normal subjects with application to the interpretation of visual neglect. *Neuropsychologia*. 1990; 29:619–628.
- Mark VS, Kooistra CA, Heilman KM. Hemispatial neglect affected by non-neglected stimuli. *Neurology*. 1988; 38:1207–1211. [PubMed: 3399068]
- Marshall JC, Halligan PW. When right goes left: An investigation of line bisection in a case of visual neglect. *Cortex*. 1989; 25:503–515. [PubMed: 2805737]
- Marshall JC, Halligan PW. A study of plane bisection in four cases of visual neglect. *Cortex*. 1991; 27:277–284. [PubMed: 1879156]
- Mennemeier M, Vezev E, Chatterjee A, Rapcsak SZ, Heilman KM. Contributions of the left and right cerebral hemispheres to line bisection. *Neuropsychologia*. 1997; 35:703–715. [PubMed: 9153033]
- Ogden, JA. The neglected left hemisphere and its contribution to visuo-spatial neglect. In: Jeannerod, M., editor. *Neurophysiological and neuropsychological aspects of spatial neglect*. Amsterdam: North-Holland; 1987. p. 215-234.
- Rapcsak SZ, Verfaellie M, Shepherd-Fleet W, Heilman KM. Selective attention in hemispatial neglect. *Archives of Neurology*. 1989; 46:178–182. [PubMed: 2916956]
- Robertson IH, North N. Fatigue versus disengagement in unilateral neglect. *Journal of Neurology, Neurosurgery, and Psychiatry*. 1993; 56:717–719.
- Robertson LC, Delis DC. Part whole processing in unilateral brain damaged patients: dysfunction of hierarchical organization. *Neuropsychologia*. 1986; 24:363–370. [PubMed: 3736818]
- Robertson LC, Lamb MR. Neuropsychological contributions to part-whole organization. *Cognitive Psychology*. 1991; 23:299–332. [PubMed: 2055002]
- Schenkenberg T, Bradford DC, Ajax ET. Line bisection and unilateral visual neglect in patients with neurologic impairment. *Neurology*. 1980; 30:509–517. [PubMed: 7189256]
- Tegner R, Levander M. The influence of stimulus properties on visual neglect. *Journal of Neurology, Neurosurgery, and Psychiatry*. 1991; 54:882–886.

Werth R, Poppel E. Compression and lateral shift of mental coordinate systems in a line bisection task. *Neuropsychologia*. 1988; 26:741–745. [PubMed: 3211292]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

RIGHT HEMISPHERE LESIONS

LEFT HEMISPHERE LESIONS

FIG. 1.
Lesions plots for RHL and LHL patients with available CT and MRI scans.

FIG. 2.

Graph showing the absolute percentage of error score for center estimation stimuli. Stimulus sizes a thru e correspond to the plane sizes a thru e. The graph reveals a curvilinear relationship between the percentage of error and stimulus size for RHL patients.

FIG. 3.

(a–d) Composite line graphs of the percentage of error score by stimulus size for individual RHL patients. (a) Patients with U-shaped plots, (b) patients with positively skewed plots, (c) patients with negatively skewed plots, and (d) patients with variable plots. The thick dark line in each graph refers to the upper 99% confidence limit for NC subjects. Patients in (a) include Nos. 6, 16, 33, 34, 36, 45, and 50. Patients in (b) include Nos. 19 and 52. Patients in (c) include Nos. 1 and 49. Patients in (d) include Nos. 17, 31, 39, 43, 53, and 54.

FIG. 4.

(a and b) Composite line graphs of the percentage of error score by stimulus size for individual LHL patients. (a) Patients with positively skewed plots (one LHL patient had a negatively skewed plot which is not shown) and (b) patients with variable plots. The thick dark line in each graph refers to the upper 99% confidence limit for NC subjects. Patients in (a) include Nos. 40, 42, 44, and 56. Patients in (b) include Nos. 32 and 47.

TABLE 1

Mean Percentage Error Scores

		Task			
		Cancellation			
Group	Size	Center estimation	32	Item 64	Item
NC (<i>n</i> = 11)	1	5.80 (3.3)	0	(0)	.71 (.82)
	2	5.09 (1.6)			
	3	6.66 (2.8)	0	(0)	.28 (.53)
	4	6.26 (4.2)			
	5	7.05 (2.9)	0	(0)	.28 (.72)
RHL (<i>n</i> = 20)	1	13.23 (6.5)	3.39	(4.2)	7.77 (7.8)
	2	10.16 (3.8)			
	3	10.79 (4.6)	1.04	(1.5)	3.52 (3.7)
	4	15.62 (13.6)			
	5	19.37 (17.0)	2.60	(7.6)	6.77 (11.9)
LHL (<i>n</i> = 11)	1	9.78 (6.1)	.31	(.66)	1.41 (3.3)
	2	7.04 (3.2)			
	3	6.92 (1.3)	0	(0)	.55 (.98)
	4	5.48 (2.0)			
	5	6.55 (3.27)	0	(0)	.55 (1.28)

Note. NC, normal controls; RHL, right hemisphere lesioned; LHL, left hemisphere lesioned. Size 1 = 6.16 cm²; 2, 208.28; 3, 1205.28; 4, 5134.5; 5, 11,056.50 cm². Standard deviations are in parentheses.

TABLE 2

Directional Biases on Center Estimation Tasks

Plane size	Groups									
	NC		RHL		LHL					
	l	r	l	r	l	r	l	r	l	r
Horizontal biases										
1	19	5**	42	18**	12	19				
2	16	12	25	31	7	22**				
3	13	17	12	48**	20	13				
4	11	22	14	40**	17	13				
5	8	25**	12	42**	17	13				
Vertical bias										
	b	a	b	a	b	a				
1	4	12	31	17	17	10				
2	7	24**	19	41**	14	16				
3	9	23**	27	32	17	15				
4	17	15	21	32	12	16				
5	11	22	26	27	14	16				

Note. Contents refers to the number of trials where marks were placed to the left (l), right (r), below (b), or above (a) true center. NC, normal controls; RHL, right hemisphere lesions; LHL, left hemisphere lesion.

* Significantly different from chance $p < .05$,
** $p < .001$.

TABLE 3

Directional Biases on Cancellation Tasks

Size	NC		RHL		LHL	
	1	r	1	r	1	r
Horizontal biases						
1	6	2	14	32**	2	4
3	2	1	10	26**	3	3
5	1	2	5	24**	0	2
Vertical bias						
	b	t	b	t	b	t
1	3	5	15	30**	4	3
3	0	3	7	24**	3	3
5	0	3	12	19	0	2

Note. Contents refer the raw number of trials in which more items were cancelled on the left (l), right (r), bottom (b), or top (t) half of the page. NC, normal controls; RHL, right hemisphere lesions; LHL, left hemisphere lesion.

* Significantly different from chance $p < .05$,

** $p < .001$.