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A kinematic analysis of distractor interference effects during visually guided action in spatial neglect

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Abstract

Patients with left spatial neglect following right hemisphere damage may show anomalies in ipsilesional-limb movements directed to targets on their affected side, in addition to their characteristic perceptual deficits. In this study we examined the extent to which visually guided movements made by neglect patients are susceptible to interference from concurrent visual distractors on the contralesional or ipsilesional side of a designated target. Eleven right hemisphere patients with visual neglect, plus 11 matched healthy controls, performed a double-step movement task upon a digitizing tablet, using their ipsilesional hand to respond. On each double-step trial the first component of the movement was cued to a common central target, whereas the second component was cued unpredictably to a target on either the contralesional or ipsilesional side. On separate trials lateral targets either appeared alone or together with a concurrent distractor in an homologous location in the opposite hemispace. In addition to being significantly slower and more error prone than controls, neglect patients also exhibited a number of interference effects from ipsilesional distractors. They often failed to move to left targets in the presence of a right-sided distractor, or else they moved to the distractor itself rather than to a contralesional target. The initial accelerative phase of their movements to contralesional targets tended to be interrupted prematurely, and they spent significantly more time in the terminal guidance phase of movements to contralesional targets in the presence of an ipsilesional distractor. In contrast, contralesional distractors had little effect on patients' movements to ipsilesional targets. We conclude that right hemisphere damage induces a competitive bias that favors actions to ipsilesional targets. This bias affects multiple stages of processing within the visuomotor system, from initial programming through to the final stages of terminal guidance. (*JINS*, 2001, *7*, 334–343)

Keywords: Interference effects, Right hemisphere, Selective attention, Spatial neglect

INTRODUCTION

The disorder of *spatial neglect* typically arises after damage to the right cerebral hemisphere in humans (Critchley, 1953; Vallar & Perani, 1986). It manifests as a failure to respond to or orient toward sensory events arising from the contralesional side of space (Robertson & Marshall, 1993). In some cases, patients may exhibit the phenomenon of *extinction*, in which detection of contralesional stimuli is impaired in the presence of simultaneous ipsilesional stimuli, despite normal performance for isolated sensory events on either side (Bender, 1952). The preserved performance with single contralesional stimuli in extinction patients suggests that afferent transmission of sensory information on the affected side is relatively preserved, with the deficit arising at some later attentive stage of perceptual processing (Driver & Mattingley, 1998).

In addition to their contralesional attentional deficits, right hemisphere patients with left neglect or extinction may also be impaired in initiating or executing movements toward targets located contralesionally, even when they use their nonparetic, ipsilesional hand (Behrmann & Meegan, 1998; Heilman et al., 1985; Mattingley et al., 1992, 1994, 1998a, 1998b). There has been debate over whether this direction-specific impairment of limb movement in neglect is due to a perceptual deficit in detecting contralesional targets, a motor deficit in moving toward them, or some combination of the two (for a full discussion of this debate, see Mattingley

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& Driver, 1997). Recent models, however, have suggested that any dissociation between sensory and motor processes underlying complex goal-directed behavior is likely to be relative rather than absolute (Mattingley & Driver, 1997). Extensive feedforward and feedback loops within sensorimotor circuits serve to combine input- and output-related activity across multiple levels of the central nervous system (e.g., Milner & Goodale, 1995). Thus, rather than attempting to isolate sensory and motor aspects of performance in patients with neglect and extinction (cf. Bisiach et al., 1990; Tegnér & Levander, 1991), we have studied the effects of varying the sensory demands of a task while holding the motor requirements constant, and *vice versa* (Mattingley et al., 1998a, 1998b; see also Behrmann & Meegan, 1998). In the present study we extended this earlier work by examining patients' ability to generate visually guided hand movements to contralesional and ipsilesional targets that could appear alone, or in the presence of a visual distractor located on the opposite side, as in standard tests for extinction. Our aim was to assess the effects of concurrent visual distractors on motor responses to contralesional *versus* ipsilesional targets.

In a typical, cluttered environment extraneous items compete with target objects for selective attention and the control of action (Tipper et al., 1998). In an effort to mimic these real-world conditions numerous investigators have devised tasks in which participants are required to move to a target location while ignoring distractors at other locations (e.g., Chieffi et al., 1993; Tipper et al., 1992, 1997). Recently we conducted a study of visually guided movement in a group of right hemisphere patients with left neglect (Mattingley et al., 1998a). Our aim was to test the hypothesis that competing ipsilesional stimuli may interfere with left neglect patients' movements toward contralesional targets during goal directed movements. Patients performed a sequence of movements (button-presses) that were cued by the sequential illumination of target LEDs. Each target LED occurred either in isolation (target-only conditions) or in the presence of a distractor LED on the opposite side of the responding hand (target-plus-distractor conditions). In target-only conditions there was no difference in the speed of patients' movements to contralesional and ipsilesional targets. In contrast, in target-plus-distractor conditions patients were significantly slower to move to contralesional *versus* ipsilesional targets, when these could not be preprogrammed at the beginning of the sequence. Thus ipsilesional distractors evidently interfere with movements directed toward contralesional targets, whereas contralesional distractors have no such effect upon movements to ipsilesional targets.

Broadly similar results were reported by Behrmann and Meegan (1998) in their study of visually guided reaching in left neglect patients. They used a task developed by Tipper et al. (1992), in which participants were required to reach from a central start key to press one of three target keys located to the left and right, and immediately above, a start key. On target-alone trials a single key was cued by a red LED; on target-plus-distractor trials one of the remaining two keys was cued (by a yellow LED) in addition to the target. Behrmann and Meegan found that reaches to left targets in target-alone trials were initiated more slowly than reaches to central and right-sided targets, suggesting a general impairment of contralesional target selection. More importantly, they also found that a concurrent distractor significantly slowed the initiation of reaches made by neglect patients, but only when the distractor appeared on the right of the designated target and not when it appeared on the left (contralesional) side.

On the basis of these findings, we have proposed that motor programs for responses directed towards contralesional and ipsilesional stimuli compete for the control of action, and that unilateral damage induces a competitive bias that favors the selection of ipsilesional stimuli as targets for movement (Mattingley et al., 1998a). When a contralesional target occurs in isolation it is selected by default because there is no ipsilesional competitor; under such conditions, therefore, patients' movements can be relatively unimpaired. In contrast, when bilateral stimuli occur concurrently the more ipsilesional one has a strong competitive advantage and thus tends to dominate the motor system. Top-down control may be exerted to overcome the competitive bias (e.g., when the target is distinguished from the distractor by its color or shape), but this process takes time and thus prolongs movement initiation and completion.

In the present study we examined a group of left neglect patients on a task that required visually guided movements to left- and right-sided targets. Whereas previous studies of distractor interference have measured only the overall time required to initiate and complete a movement (e.g., Behrmann & Meegan, 1998; Mattingley et al., 1998a, 1998b), in the present study we recorded limb position continuously in order to derive kinematic parameters. These parameters permit independent quantification of the initial accelerative (force production) and later decelerative (guidance) phases of movement. We previously showed that severe neglect patients exhibit a prolonged accelerative phase for predictable movements directed to contralesional targets, together with an abnormal emphasis on visual guidance for movements toward ipsilesional targets (Mattingley et al., 1994). However, our previous study did not employ visual distractors, and the locations of targets were always predictable, being specified before the beginning of each trial. For the present study we also devised a new "double-step" pointing task in which contralesional and ipsilesional movements are initiated from a common central start position. This new design eliminated any unusual control processes that may have been invoked by our previous sequential movement paradigms (Mattingley et al., 1992, 1994, 1998a), in which each new movement had to be initiated from a different start position in left or right hemispace (cf. Konczak & Karnath, 1998). Finally, targets and distractors were distinguished on the basis of their color (yellow *vs.* red) rather than their location (left *vs.* right), thus overcoming any potential demand characteristics involved in asking patients to move toward their "bad" side.

If neglect involves a competitive bias favoring ipsilesional over contralesional actions, then right hemisphere patients should be slower to perform movements to left *versus* right targets. Specifically, we predicted that patients would make significantly more errors of movement toward distractors on the ipsilesional *versus* contralesional side. We also predicted that patients would be impaired in the initial accelerative phase of contralesional movements, particularly in the presence of a concurrent ipsilesional distractor; and that there would be greater interference in the decelerative phase of contralesional movements produced in the presence of an ipsilesional distractor than in movements to ipsilesional targets with a contralesional distractor.

METHODS

Research Participants

Eleven patients with right hemisphere damage and left unilateral neglect, and 11 age- and sex-matched controls, were tested. There was no significant difference between the mean ages of patients (60.3 years) and controls (60.5 years) [$F(1,20) < 1$]. All participants gave their informed consent prior to commencement of the experimental tasks. Patients were excluded if they had bilateral cerebral lesions, dementia, severe gaze palsy, or previous neurological illness. The presence of a right hemisphere lesion was confirmed by neurological examination and CT scan. Age, sex and clinical details for the patients are shown in Table 1. The presence of neglect in patients was established by their performance on standard clinical tests, which consisted of Albert's line cancellation task (Albert, 1973), the star cancellation task from the Behavioral Inattention Test (Wilson et al., 1987), and a line bisection task (Mattingley et al., 1993). The line bisection task consisted of 10 horizontal lines of varying lengths (from 80 mm to 170 mm) drawn on a sheet of A4 paper. The patient was shown each line in isolation and asked to mark the midpoint with a pencil held in the ipsilesional (right) hand. The extent of any deviation from the true midpoint was measured in millimetres and an average deviation score over the 10 lines was obtained (positive scores indicate a rightward bias; negative scores indicate a leftward bias). All screening tests were presented directly in front of the patient on a flat table top. As indicated in Table 1, all patients showed a mean rightward bisection error, and an abnormal number of omissions on at least one of the two cancellation tests. (Note that in all cases the number of omissions in cancellation tests was greater on the contralesional half of the page.)

Apparatus

Participants' hand movements were measured via a noninking, electronic pen moved over the active surface of a Wacom SD420 digitizing tablet. The tablet measured 420 mm × 420 mm and had an active surface of 305 mm × 305 mm. The tablet sat on a flat table-top, and was inclined toward the participant at an angle of 7° from horizontal to ensure a comfortable drawing surface. When in contact with the tablet surface the pen tip sampled at a rate of 200 Hz. Data were recorded in the *X* (horizontal) and *Y* (radial) coordinates and were accurate to 0.02 mm. A perspex cover was placed over the active surface of the tablet. Under the perspex cover was a white sheet onto which were printed four unfilled black circles with a line thickness of 0.5 mm and a diameter of 15 mm. The circles were positioned at the endpoints and intersection of an imaginary 'T' that had its radial limb aligned with the participants' midsagittal axis (see Figure 1). A *start* circle was located at the base of the 'T', closest to the participant's body. An *intermediate* circle was

Table 1. Age, sex and clinical details for left neglect patients

						Clinical tests		
Patient no.	Age	Sex	Lesion	Post stroke (weeks)	Visual fields	AL (/36)*	SC (/54)**	LB (mm)†
1	33	M	TP	11	LHH	12	13	44.8
2	67	M	TP	4	LHH	36	47	25.3
3	57	M	Thal.	5	NAD	33	47	1.2
4	65	M	P	2	NAD	19	8	4.1
5	73	F	TP	3	LHH	12	15	14.2
6	77	F	BG	3	NAD	33	52	3.3
7	81	F	FP	4	NAD	14	7	20.6
8	67	M	P	2	NAD	22	20	6.4
9	55	M	O/Mb	1	LHH	27	40	8.3
10	49	F	FP	12	LHH	34	49	16.3
11	72	F	TP	2	LHH	23	13	11.6

*$M = 24.1$; $SD = 9.1$. **$M = 28.3$; $SD = 18.5$. †$M = 14.2$; $SD = 12.6$.

Note. TP = temporoparietal; O = occipital; P = parietal; Mb = midbrain; BG = basal ganglia; FP = frontoparietal; Thal. = thalamus; LHH = left homonymous hemianopia; NAD = no abnormalities detected; AL = number of targets canceled on Albert's lines test; SC = number of targets canceled on Star Cancellation test; LB = mean rightward error (mm) on line bisection task.

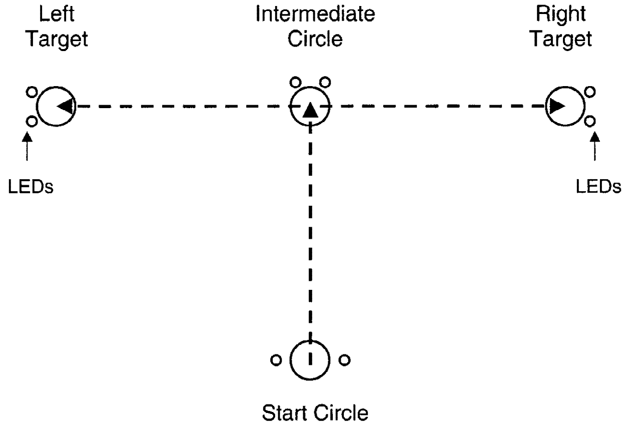

Fig. 1. Schematic of the double-step movement task used in the study. Trials commenced when the participant placed the pen-tip inside the start circle. LEDs located adjacent to the Intermediate circle then illuminated to provide a cue for the participant to begin the first component of the double-step movement. These LEDs were extinguished as soon as the pen-tip entered the intermediate circle; at the same time a yellow LED adjacent to a target circle on either the left or right was illuminated alone (on target-only trials), or concurrently with a red LED on the opposite side (on target-plus-distractor trials). Broken black lines indicate idealized trajectories, and were not present in the actual display. (Drawing not to scale.)

located in a radial line 125 mm from the *start* circle. The two *target* circles were located 100 mm to the left and right side of the intermediate circle. Yellow (target) and red (distractor) light emitting diodes (LEDs) were fixed on the perspex sheet adjacent to each of the circles (see Figure 1). The start and intermediate circles were each illuminated by two yellow LEDs. Each of the two target circles had both a yellow (target) and a red (distractor) LED adjacent to it.

Procedure

A Toshiba T3100 SX laptop computer recorded pen coordinates in the X and Y axes during the task. Participants were seated approximately 200 mm directly in front of the digitizing tablet, so that both target circles were within easy reach. All participants used their ipsilesional (right) hand to hold the pen. They completed the clinical tests and the experimental task in a single session, with the opportunity for short rest breaks as required.

In the main experimental task, participants were asked to move the pen tip in a double-step movement, beginning from the start circle located closest to the body and proceeding radially to the intermediate circle located at the intersection of the imaginary ‘T.’ After entering the intermediate circle, the pen tip then had to be moved into the left or right target circle, as indicated by the LED cues. Participants were told to move as quickly and as smoothly as possible without making any errors.

The sequence of events for each trial was as follows. Both of the yellow LEDs next to the start circle pulsed on and off as a cue for the participant to place the pen tip inside the start circle. As soon as the pen tip touched the active surface within the area of the start circle, both LEDs were extinguished and at the same time the two yellow LEDs adjacent to the intermediate circle were illuminated. These provided a central cue for participants to commence the first component of the double-step movement by moving the pen tip over the active surface of the tablet and into the intermediate circle. This initial radial movement was included to encourage participants to keep their eyes and attention directed to a point midway between the two target loci, so that the subsequent target and distractor events would initially appear at equal retinal eccentricities to the left and right. As soon as the pen tip entered the intermediate circle, the adjacent LEDs were extinguished, and simultaneously one or two of the LEDs adjacent to the target circles were illuminated. On target-only trials, a single yellow LED illuminated next to a target circle on either the left or right side. On target-plus-distractor trials a single yellow LED illuminated next to a target circle on one side, and a red LED (the distractor) illuminated simultaneously on the other. To assist patients to distinguish targets from distractors, yellow target LEDs pulsed on and off at a rate of approximately 5 Hz, whereas red distractor LEDs were continuously illuminated. Participants were instructed to move as quickly as possible to any yellow (target) LED, and to ignore any red (distractor) LED. Recording of movement commenced as soon as the pen tip entered the intermediate circle and stopped after the patient had successfully moved the pen into a target circle, or after 10 s.

The experiment consisted of two possible target sides (left, right), and two distractor conditions (target-only, target-plus-distractor), yielding four different trial types. There were 12 trials in each block, with three repetitions for each of the four trial types, all presented in a random order. Targets appeared with equal probability on the left and right sides. Each participant completed six blocks, yielding 72 trials in total. Participants were also given a practice block of trials at the beginning of the experiment, the data from which were not analyzed. Trials in which participants failed to move to a target, or in which they moved to an incorrect location, were recorded but not repeated.

Data Analysis

Pen-tip coordinates were sampled at 200 Hz and stored for subsequent analysis offline. Kinematic analyses were restricted to those trials in which the pen was moved into the correct target circle. Trials in which a participant failed to move into the correct target circle were recorded as spatial errors, and were not considered in the kinematic analyses. Analysis occurred in a number of stages. In the first stage the beginning and end of each movement were determined interactively. The data were then low-pass filtered (10 Hz cut-off) to remove quantization noise in the digitized signal, using a recursive, dual-pass, second-order Butterworth filter. The dual-pass removed any phase lag (see Mattingley et al., 1994 for further details). Displacement data in the horizontal (X) axis were then differentiated to obtain a velocity profile for each trial. In the second stage, automatic algorithms were used to determine kinematic features of the displacement and velocity functions.

In this paper we report results for the following variables: *initiation time* (the time for which the pen tip was held stationary inside the intermediate circle prior to movement toward the left or right target); *time to peak velocity* (the time in milliseconds to reach peak velocity for movements from the Intermediate circle to a peripheral target); *time from peak to zero* (the time in milliseconds spent decelerating from peak velocity to zero velocity during movements to lateral targets); and *movement time* (the total time taken to move from the intermediate circle to a peripheral target). These variables provide unique measures of the overall time for initiation and execution of lateralized movements, in addition to the distinct components of acceleration and deceleration. Data for each of these four dependent variables were analyzed using mixed-design ANOVAs, with a between-subjects factor of group (patients, controls), and within-subjects factors of target side (left, right) and distractor condition (target-only, target-plus-distractor).

RESULTS

For ease of exposition we consider the error data and kinematic data separately below.

Errors

Any trial in which the pen tip did not terminate inside the correct target circle was counted as an error. There were four types of error: (1) *movement to distractor*, in which participants initially moved toward a distractor instead of a target; (2) *no movement*, in which participants failed to initiate a lateralized movement from the intermediate target; (3) *hypometric movement*, in which a correct movement was initiated but fell short of the target; and (4) *pen lifts*, in which the participant lifted the pen off the surface of the digitizing tablet during the execution of the movement, thus interrupting data sampling.

Considering the combined data from patients and healthy controls, errors constituted approximately 4.0% of all trials. The error data are shown in Table 2, tabulated separately for the two groups according to the type of error made. Due to the relatively small numbers of errors overall, data were initially pooled across error type for analysis. Patients made significantly more errors overall than controls [58 *vs.* 13; $\chi^2(1) = 29.74$, $p < .0001$]. For controls there were no significant differences in the number of errors made as a function of target side (left *vs.* right) or distractor condition (target-only *vs.* target-plus-distractor). In contrast, patients made significantly more errors for left targets than for right targets [44 *vs.* 14; $\chi^2(1) = 16.63$, $p < .0001$]. This disadvantage for left *versus* right targets was evident for both target-only trials [17 *vs.* 6; $\chi^2(1) = 5.56$, $p < .05$] and for target-plus-distractor trials [27 *vs.* 8; $\chi^2(1) = 11.22$, $p < .001$]. Considering the left target conditions, there was a nonsignificant trend for patients to make more errors in target-plus-distractor trials than target-only trials [27 *vs.* 17; $\chi^2(1) = 2.53$, $p = .11$]. This distractor effect was not evident in the right target conditions [8 *vs.* 6; $\chi^2(1) < 1$].

One feature of the patient error data that is worthy of particular mention is the number of trials in which they moved inappropriately toward a distractor location (i.e., in a direction *opposite* to that indicated by the target). This occurred on 14 trials with a left target plus right distractor, but on only one trial with a left target alone [$\chi^2(1) = 11.71$, $p < .001$]. In contrast, there was no significant distractor effect for right targets [$\chi^2(1) = 2.26$, $p > .10$]. Overall patients made significantly more incorrect movements on target-plus-distractor trials when the target appeared on the left side than when it appeared on the right [14 *vs.* 4; $\chi^2(1) = 5.82$, $p < .05$]. Thus neglect patients seemed particularly prone to generating movements toward distractors when these were located on the ipsilesional side, even though the distractors were always distinguished from targets by their unique color and steady illumination. This phenomenon of selecting the ipsilesional distractor as the initial target for a movement is illustrated in Figure 2, which shows sample displacement data from four separate trials with a left target plus right distractor, completed by Patient 8 (see Table 1). After correctly moving the pen tip from the start circle to

Table 2. Numbers of errors made by neglect patients and controls as a function of target side (Left, Right) and distractor condition. T = target-only; T+D = target-plus-distractor

	Patients				Controls			
	Left target		Right target		Left target		Right target	
Error type	T	T+D	T	T+D	T	T+D	T	T+D
Movement to distractor	1	14	0	4	0	5	1	7
No movement	7	6	1	1	0	0	0	0
Hypometric movement	3	2	2	0	0	0	0	0
Pen lifts	6	5	3	3	0	0	0	0
Total	17	27	6	8	0	5	1	7

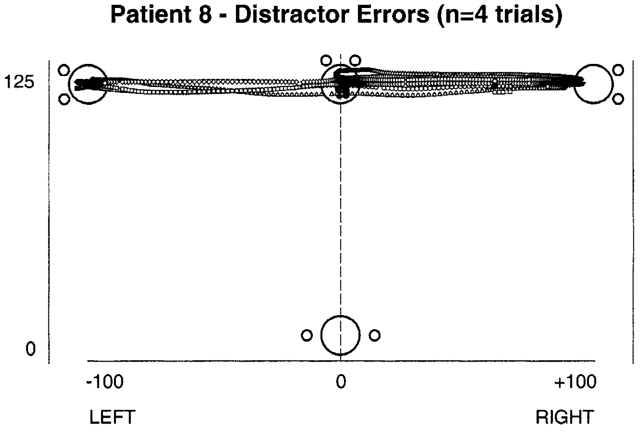

Fig. 2. Examples of distractor errors made by Patient 8 (refer to Table 1) in trials with a left target and right distractor. The figure shows traces from four separate trials. Each trace represents the trajectory of the pen-tip during a single trial. Upon entering the intermediate circle (where kinematic recording began), the patient initially moved to the distractor on the right side before spontaneously correcting the error and moving to the target on the left. Symbols comprising each trace represent sampling intervals of 5 ms. Horizontal and radial axes show displacement in millimeters. (Drawing not to scale.)

the intermediate circle along a radial line in the midsagittal axis, the patient initially moved toward the right-sided distractor, spontaneously recognized the error, and corrected it by moving the pen tip back over the intermediate circle to the left target.

Temporal and Kinematic Data

Recall that only those trials in which participants moved the pen tip into the correct target (without first moving toward a distractor) were included in the kinematic analyses. Means and standard errors for each of the kinematic variables are plotted separately for the two groups as a function of target side in Figure 3. The white bars represent data from target-only conditions and the black bars represent data from target-plus-distractor conditions.

Initiation time

Initiation time is the time the participant held the pen tip stationary inside the intermediate circle before initiating a leftward or rightward movement. Note that in the double-step movement task employed here the target LED was illuminated as soon as the pen tip crossed into the intermediate circle. Thus preparation for the lateral movement (leftward or rightward) cued by the target LED could begin prior to the completion of the first radial movement. Because the initiation times measured here only include the period for which the pen *remained stationary* prior to the first lateral movement, they are considerably shorter than would be expected for standard reaction times in such a choice task.

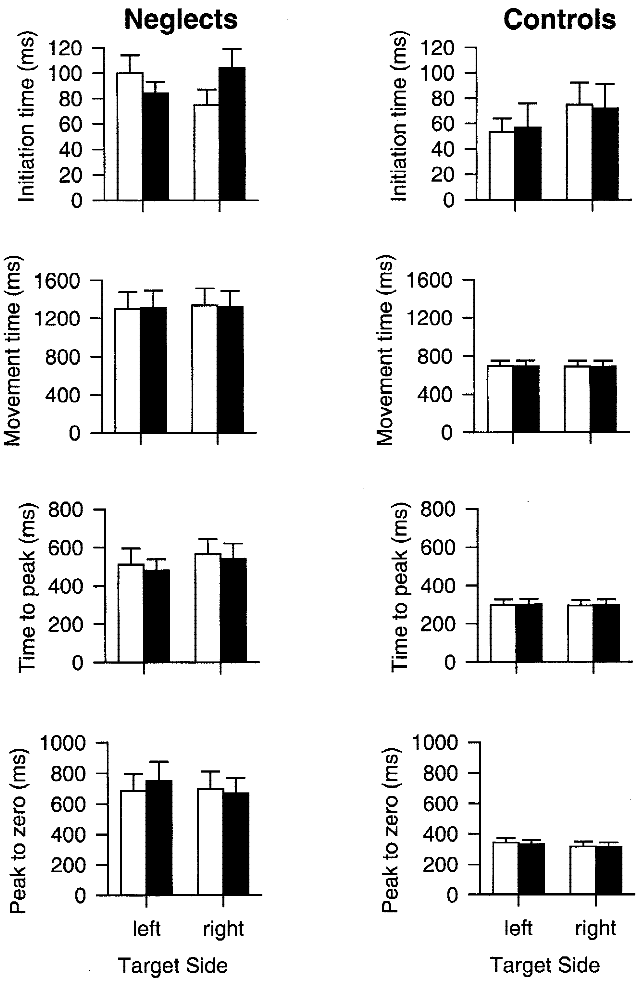

Fig. 3. Means and standard errors for each of the kinematic variables obtained for visually guided movements to left and right targets. Data are plotted separately for neglect patients (left panels) and controls (right panels) as a function of target side. *White bars*: target-only trials. *Black bars*: target-plus-distractor trials.

The only significant effect to emerge from the ANOVA on initiation times was a three-way interaction of Group × Target Side × Distractor Condition ($F(1,20) = 5.16$, $p < .05$]. To investigate this interaction, separate two-way ANOVAs were conducted on control and patient data, with the factors of target side and distractor condition. For controls, movements to left targets were initiated significantly earlier than movements to right targets [55 ms *vs.* 73 ms; $F(1,10) = 5.93$, $p < .05$]. However, there was no significant main effect of distractor condition and no interaction. For neglect patients, the control pattern of faster initiation times for left *versus* right targets was absent [$F(1,10) < 1$]. In addition, unlike controls neglect patients showed a significant interaction between Target Side × Distractor Condition [$F(1,10) = 4.86$, $p = .05$]. To further examine this interaction, two one-way ANOVAs were conducted separately on data from left target and right target conditions, with the factor of distractor condition. Patients took 29 ms longer to initiate a movement to a right-sided target in the presence of a left distractor (104 ms), than to a right-sided target alone [75 ms; $F(1,10) = 6.91$, $p < .05$]. Paradoxically, there was no significant distractor effect on movement initiation time for left targets [$F(1,10) = 1.57$, $p >$ .05].

Movement time

Movement time was defined as the overall time spent executing a movement from the intermediate circle into one of the two lateral targets. Across all conditions, patients were significantly slower to execute their movements than controls [1316 ms *vs.* 690 ms, $F(1,20) = 11.15$, $p < .01$]. Although these movement times may seem rather long for a lateral movement of only 100 mm, recall that the target circles were relatively small (10 mm in diameter), thus requiring considerable reliance on visual guidance. Moreover, our instructions to participants emphasized the importance of accuracy. There were no other significant main effects or interactions. Thus although patients were generally slow to execute movements in this task, the *overall* time they spent executing movements was unaffected by the laterality of targets or the presence of a concurrent visual distractor.

Time to peak velocity

The time taken to reach peak velocity provides an index of the initial accelerative phase of movement. Patients were 225 ms slower overall to reach peak velocity compared with normal controls [525 ms *vs.* 300 ms; $F(1,20) = 8.51$, $p <$ .01]. In addition, considering the data from both patients and controls, movements to right targets took 27 ms longer to reach peak velocity than movements to left targets [426 ms *vs.* 399 ms; $F(1,20) = 9.46$, $p < .01$]. The only other significant result was a two-way interaction of Group × Target Side [$F(1,20) = 11.35$, $p < .01$]. Separate one-way ANOVAs were conducted on data from each group, with the factor of target side (collapsed across distractor condition). For controls there was no significant difference in the time required to reach peak velocity for movements to left *versus* right targets [301 ms *vs.* 298 ms; $F(1,10) < 1$]. Thus, the time spent by controls in the initial accelerative phase of movement was equivalent for movements to left and right targets. In contrast, neglect patients departed significantly from this normal symmetrical pattern, reaching peak velocity significantly earlier for movements to left targets (496 ms) than for right targets [554 ms; $F(1,10) = 11.16$, $p < .01$].

Peak velocity to zero

The time from peak velocity to zero velocity provides an index of the time spent in the decelerative phase of movement. Patients spent significantly longer overall in the decelerative phase of movement compared with controls [700 ms *vs.* 326 ms; $F(1,20) = 10.72$, $p < .01$], implying an abnormal reliance on terminal guidance in their movements. The only other significant effect was a three-way interaction of Group × Target Side × Distractor Condition [$F(1,20) = 4.60$, $p < .05$]. To explore this interaction, two-way ANOVAs with factors of target side and distractor condition were conducted separately on data from each group. For controls there was a near-significant main effect of target side [$F(1,10) = 4.68$, $p = .056$], with shorter deceleration times for right targets than for left targets (315 ms *vs.* 337 ms). There was no significant main effect of distractor condition and no significant two-way interaction. For neglect patients, on the other hand, there was a trend toward significance in the two-way interaction of Target Side × Distractor Condition [$F(1,10) = 4.05$, $p = .07$]. As shown in Figure 3, patients tended to decelerate over a longer period when moving to left targets with a right distractor (746 ms) than when moving to left targets alone (687 ms), suggesting some degree of interference from irrelevant ipsilesional stimuli in the terminal guidance phase of movements to contralesional targets. In contrast, the decelerative phase was somewhat *shorter* for movements to right targets with a left distractor (669 ms), compared with movements to right targets alone (697 ms).

Comparison of kinematics in hemianopic and nonhemianopic patients

Six neglect patients in our sample of 11 had a left homonymous hemianopia. Since the potential contribution of visual field cuts to motor performance in our task is unclear, we conducted separate analyses in which we compared motoric indices directly for hemianopic and nonhemianopic individuals. Separate ANOVAs were performed on *initiation time*, *movement time*, *time to peak velocity*, and *peak to zero velocity* for the patient data only, using the same within-subjects factors as the analyses above, plus the new between-subjects factor of patient group (hemianopic *vs.* nonhemianopic). There were no significant main effects or interactions involving the factor of patient group for any of the analyses. Our tentative conclusion, therefore, is that the presence of a left hemianopia does not contribute significantly to the motor performance of neglect patients on this particular task.

DISCUSSION

The purpose of this study was to examine the effects of visual distractors on the kinematics of visually guided movements in patients with right hemisphere damage and left neglect. The patients showed significant visual neglect on a range of standard clinical tests (see Table 1), and were thus predicted to exhibit impairments when required to execute movements to left-sided targets, as observed in previous studies (e.g., Behrmann & Meegan, 1998; Mattingley et al., 1992, 1994, 1998a). In addition to making significantly more movement errors than controls overall, the neglect patients also made significantly more errors in left-target trials than in right-target trials. This pattern was illustrated most strikingly in the target-plus-distractor conditions, in which patients often moved inappropriately toward the right-sided (ipsilesional) distractor, before correcting their mistake and moving toward the left-sided (contralesional) target (see Figure 2). These ipsilesional errors are particularly striking since the distractors were always clearly distinguished from targets by their color, in addition to being less salient than targets because of their continuous illumination (compared with the flickering target stimuli).

These results lend support to our prediction that actions programmed toward ipsilesional stimulus events may be triggered earlier or more readily than those toward contralesional events, even when such actions are clearly contrary to task demands. In a previous study (Mattingley et al., 1998a) we suggested that motor programs for responses directed towards visual targets compete for the control of action, and that unilateral damage induces a competitive bias that favors the selection of ipsilesional over contralesional stimuli as targets for movement. When a contralesional target occurs in isolation it is selected by default because there is no ipsilesional competitor, but when bilateral stimuli occur concurrently the more ipsilesional one has a strong competitive advantage and thus tends to be selected for action. In the context of the present task we would argue that right-sided visual stimuli enjoyed a competitive advantage over contralesional stimuli in affording goal directed actions. Consequently patients were inclined to select movements toward the ipsilesional side, even when this was clearly inappropriate to the task demands.

There were also two direction-specific anomalies in the kinematic profiles of patients' movements. Whereas normals spent an equivalent period in the initial accelerative phase of movement regardless of target side, patients reached peak velocity significantly earlier for contralesional *versus* ipsilesional movements. This implies either an abnormal interruption to the initial force-production phase of leftward movements, or a lower peak force associated with this phase (cf. Mattingley et al., 1994). In the absence of an index of peak acceleration it is not possible to distinguish unambiguously between these two possibilities, but future studies could address this interesting issue. In any case, the pattern was apparent in both target-only and target-plus-distractor trials, and thus was not subject to significant interference from concurrent ipsilesional distractors. In contrast, there was a significant effect of ipsilesional distractors on time from peak velocity to zero in neglect patients. They spent significantly longer in the terminal guidance phase of movements to left targets presented with concurrent ipsilesional distractors, than to left targets presented alone. There was no such distractor effect for movements to right targets, nor was there any effect of distractors on the terminal guidance of movements made by controls. The prolonged decelerative phase for leftward movements made by neglect patients arose in the context of equivalent overall movement times to left *versus* right targets. This implies a greater reliance on visual guidance during movements to targets on the neglected side when an ipsilesional competitor is present concurrently. This result is consistent with Behrmann and Meegan's (1998) findings of ipsilesional distractor effects in neglect patients, although interestingly they only observed such effects in movement initiation times, rather than in movement execution as we found here. Our results suggest that during the terminal guidance phase of movements to contralesional targets, concurrent ipsilesional events continue to compete strongly for selection.

Patients tended to move more slowly overall compared with controls, as reflected in their significantly prolonged total movement times, and prolonged accelerative and decelerative phases of movement. These findings are consistent with previous studies of reaching in right hemisphere patients (e.g., Behrmann & Meegan, 1998; Konczak & Karnath, 1998; Mattingley et al., 1992, 1994, 1998a), and are likely to reflect a general slowing in the rate of information processing for such novel tasks, particularly when targets are small and spatial accuracy is emphasized, as in our task. It is also likely that patients suffered a deficit in their overall level of arousal due to right hemisphere pathology (Posner, 1993; Robertson, 1993; Robertson et al., 1998), which may have further hindered their performance.

Although patients' overall movement times were comparable to those found in our previous kinematic study (Mattingley et al., 1994), there were also several discrepancies. In our earlier task we found that leftward movement times were abnormally prolonged, and showed a reduced peak velocity when compared with rightward movements. There are at least two possible reasons for this discrepancy. The first concerns the starting position of the hand. In our previous study (Mattingley et al., 1994) patients performed an alternating sequence of leftward and rightward movements in each trial, with successive movements being initiated from the hemispace opposite the target. In the current study, only a *single* lateralized movement was required from the centrally located intermediate circle. Recently Konczak and Karnath (1998) also found that neglect patients were no slower to execute single pointing movements to contralesional *versus* ipsilesional targets from a constant start position (in right hemispace). There is clear evidence that movements to contralesional targets in neglect are influenced by hand-start position (cf. Duhamel & Brouchon, 1990; Mattingley et al., 1998b). Perhaps therefore the kinematic anomalies observed for contralesional actions in our sequential movement task arose because they always commenced within the *ipsilesional* hemispace, and required patients to cross the midline in order to reach contralesional targets. In the present study patients commenced their leftward and rightward movements from a common central location which corresponded to the body midline, and thus did not need to cross the midline to reach the targets.

A second possible reason for the discrepancy between the present findings and those of Mattingley et al. (1994) relates to differences between the number and pattern of movements required by the two tasks. Whereas in the present study each trial consisted of a single movement to a common central location followed by a second movement to a lateral target, in our earlier study patients performed six consecutive movements to left and right targets in a single trial. In that study we found patients' contralesional movements tended to become progressively slower throughout the sequence, such that the final movement was considerably slower than the first (see Mattingley et al., 1994, Figure 4b). We speculate that any asymmetry in the kinematics of leftward *versus* rightward movements may manifest more strongly during such sequential actions, perhaps due to an increase in spatial and temporal errors that accumulate over successive movements. Indeed, such sequential tasks have been shown to induce progressively increasing movement instability in patients with motor impairments due to basal ganglia dysfunction, such as Parkinson's and Huntington's diseases (e.g., Georgiou et al., 1995; Martin et al., 1994). This seems to us an important variable to test in future studies of motor performance in neglect.

We found no evidence that neglect patients with contralesional visual field defects performed differently on the various measures of motor performance compared to those with full visual fields. This is consistent with at least one report in the literature that suggests that neglect on perceptual tasks is not exacerbated by left homonymous hemianopia (Halligan et al., 1990). It remains possible, however, that the presence of a visual field cut could conceivably influence motor performance on other visually guided motor tasks, particularly if they involved limb movements to targets in peripheral vision. Recall that in the present task lateral targets were located 10 cm on either side of the intermediate circle, and were thus within the central few degrees of the visual field.

In the present study we recorded movement initiation times from the intermediate circle rather than from the start circle, since it was only upon entering the intermediate circle that the peripheral LEDs were illuminated, thus informing the participant of the direction (left or right) in which to move. Because the target LED was illuminated as soon as the pen tip entered the intermediate circle (i.e., prior to the end of the initial radial movement), mean initiation times were substantially shorter than would normally occur in such a two-choice response task. This advance information effectively allowed participants to program the direction of the required response in advance, thus reducing the stationary phase between successive movements.

In a future study we aim to use the same double-step task to measure visuomotor performance in neglect patients, but with a *central* bicolor LED at the intermediate location to cue leftward and rightward movements, rather than the peripheral LED cues used here. In our modified task the central cue will illuminate as the patient prepares to move from the start circle, thus allowing us to measure any asymmetry in the initial planning of double-step movements in which the first radial component is to a common central location (cf. Rosenbaum, 1994). If our model of motor competition in neglect is correct, patients should take significantly longer to initiate the first component of a double-step movement in which the second target is located on the contralesional side, compared with movements in which the second target is located on the ipsilesional side. Whatever the outcome of this future investigation, our primary interest in this study was to examine the influence of competing ipsilesional stimuli on movement *execution* to contralesional targets, and this aim was fulfilled unambiguously by our task.

In conclusion, we have shown that visually guided actions directed toward contralesional targets can be impaired in patients with left neglect after right hemisphere damage, particularly when a concurrent distractor is present on the ipsilesional side. Clearly, however, these direction-specific anomalies do not manifest themselves equally in all motor tasks, nor do they occur consistently across all kinematic variables. Further research will be needed to ascertain the extent to which these inconsistencies are attributable to task-related factors, the variables used to measure performance, or to idiosyncrasies associated with the patients themselves (e.g., severity of neglect, lesion site, chronicity, etc.; see Behrmann & Meegan, 1998; Mattingley et al., 1992, 1994, 1998a, 1998b). Nevertheless the present data do provide support for our hypothesis that motor programs for responses directed towards contralesional and ipsilesional stimuli compete for the control of action, and that unilateral damage induces a competitive bias that favors the selection of ipsilesional stimuli as targets for movement. Our data also suggest that even after a movement has been successfully initiated toward a contralesional target, ipsilesional distractors may continue to exert a competitive influence on online motor control, particularly during the terminal guidance phase of movement in which visual and proprioceptive feedback are crucial for endpoint accuracy. We conclude that the competitive bias induced by right hemisphere damage operates at multiple levels within the sensorimotor system, and may thus influence actions from the earliest levels of motor programming through to the final stages of execution and feedback control.

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