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The Role of the Hemispheres in Closed Loop Movements

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The purpose of these experiments was to determine if the two hemispheres play different roles in controlling closed loop movements. Subjects were asked to move to a narrow or wide target in the left or right hemispace. Reaction time (RT) was faster for the left arm of normals, only in the right hemispace, but there were no differences between arms in movement execution. Right but not left hemisphere stroke (CVA) patients showed longer RTs for the contralateral but not ipsilateral arm. The right CVA group's ipsilateral movement, especially to narrow targets was less accurate. The left CVA group's RT did not benefit from advanced information, but ipsilateral movement execution was normal. These results were discussed in terms of inter- as well as intrahemispheric control of programming and execution of closed loop movements.

INTRODUCTION

The differential roles of the cerebral hemispheres in controlling movement has been of interest to many investigators studying the organization and control of voluntary movements. Although historically the greater importance of the left hemisphere in motor control has been emphasized (Liepmann, 1913), more recent studies provide some evidence that the right hemisphere also plays a role (Watson, Fleet, Gonzalez-Rothi, & Heilman, 1986). Just as the appreciation of the right hemisphere's in-

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dependent role in language (Perecman, 1983) has increased our knowledge of language processing, differentiation of the individual roles of the two hemispheres in the control of voluntary movements should improve our understanding of motor processing.

While it is widely accepted that motor functions on one side of the body are mediated by the contralateral hemisphere, many studies with brain damaged patients have demonstrated that left hemisphere damage produces bilateral motor deficits on a wide variety of motor tasks including limb sequencing (DeRenzi, Motti, & Nichelli, 1980; Jason, 1985; Kimura, 1977, 1982; Kimura & Archibald, 1974; Roy, 1980), gesturing (Geschwind, 1965, 1975), aiming on a modified pursuit rotor apparatus (Wyke, 1968), and rapid unilateral and bilateral aiming movements (Haaland, Harrington, & Yeo, 1987; Wyke, 1967, 1971). Studies with normal individuals have suggested that the right hand advantage in right-handers in finger tapping (Kinsbourne & Hicks, 1978; Lomas & Kimura, 1976; Peters, 1976, 1980; Peters & Durding, 1979; Todor & Doane, 1978; Todor & Kyprie, 1980; Todor, Kyprie, & Price, 1982; Wolff, Hurwitz, & Moss, 1977) is evidence of the left hemisphere dominance for processing movements with a sequential or temporal structure. However, many of these studies in normals are confounded by the fact that the dominant hand of right-handed individuals is more practiced, so the finding of a right hand superiority may be more reflective of differential usage rather than cerebral organization (see Peters, 1976).

Factors which have been attributed to right hemisphere control include attention, intention or response set, and spatial factors. Some studies also have attempted to specify the right hemisphere's role as a function of the type of movement and whether the control is at the programming and/or execution phase. Generally speaking, attention and spatial factors can be part of the programming and the execution phases of movement while intention is considered more strictly part of programming. Motor dominance of the right hemisphere has been shown in studies with brain damaged patients where deficits are characterized by hypokinesia and bradykinesia associated by some with the right hemisphere's role in attention or intention (Heilman, 1985). Right hemisphere damage also has been shown to produce greater slowing of reaction time (RT) than left hemisphere damage (DeRenzi & Faglioni, 1965; Howes & Boller, 1975), but both of these studies confounded hand used and lesioned hemisphere. In the Howes and Boller study, the control group only used their right hand while the right brain damaged group used their right hand and the left hemisphere group used their left hand. This would not make a difference if there were no right–left hand differences, but some studies show left-handed RTs are faster in normals (Klapp, Greim, Mendicino, & Koenig, 1979; MacKenzie, 1985) which automatically gives the left hemisphere group an advantage and the right hemisphere group a disadvantage independent of which hemisphere is damaged. To our knowledge only one study has properly controlled hand used and shown slower RTs in the ipsilateral limb after right vs. left hemisphere damage. However, that study only used right hemisphere damaged patients with neglect so the effect may not apply to all patients with right hemisphere damage (Heilman, Bowers, Coslett, Whelan, & Watson, 1985). When hand used has been properly controlled in left and right hemisphere lesioned patients, both groups showed equal impairment relative to the control group (Benton & Joynt, 1958).

Still, another study using normals has emphasized that right hemisphere dominance is directly related to the task's spatial requirements (Nachson & Carmon, 1975). A left hand advantage in normal subjects also was found in a task requiring flexion of individual fingers (Kimura & Vanderwolf, 1970) and the reproduction of bilateral finger and thumb positions without visual feedback (Roy & MacKenzie, 1978). Recently, investigators have found that the left hand of normal right handers performed ballistic aiming movements better than the preferred hand (Guiard, Diaz, & Beaubaton, 1983). In this study, subjects moved their left index finger from a starting handle to a point located to the left or right without visual feedback. The findings showed that accuracy, but not RT, was better with the left hand which supported the right hemisphere's special role in executing programmed ballistic aiming movements. However, Guiard and his colleagues did not determine if nonballistic, sensory-dependent aiming movements showed the same hand effect in order to separate whether the left hand advantage was due to the type of aiming movement made (i.e., ballistic vs. nonballistic) or the fact that the aiming movement was made in a spatial context and required attention and response preparation.

Although the preceding review of research pertaining to hemispheric specialization of function in motor skills suggests that the left hemisphere is dominant for processing information with a sequential or temporal structure while the right hemisphere is more important for discrete movements in a spatial context which emphasize attention and intention, none of these descriptions have gained universal acceptance because of conflicting findings. Specifically, several studies with sequential/temporal requirements have shown that ipsilateral arm performance on tasks such as tracking on a pursuit rotor (Heap & Wyke, 1972), limb sequencing without memory components (Jason, 1983a, 1983b), maze coordination (Haaland & Delaney, 1981), and peg insertion (Haaland & Delaney, 1981; Vaughan & Costa, 1962; Wyke, 1971) were equally impaired by left or right cerebral hemisphere lesions. Furthermore, in studies with normal subjects, RT to stimuli presented in the right or left visual field either did not differ between hands (Berlucchi, Heron, Hyman, Rizzolatti, & Umilta, 1971) or was superior when information was processed by the left, but not the right, hemisphere (Dimond & Beaumont, 1973). Reported hemispheric asymmetries in attentional bias on the detection of spatial information also have not been consistently replicated (Boles, 1979; Bryden, 1976).

The apparent discrepancies in the literature regarding hemispheric asymmetry of movements ipsilateral to lesion may be due to a variety of other factors including differences among patient groups in the lesion size and locus (CT-scan data have not been provided in most studies), incidence of neglect, and differences among studies in the task being used. Because of the diversity of tasks employed for studying cerebral organization, the component processes investigated may include attention, detection, perception, retrieval, memory, response programming, decision-making, and/or execution processes, each of which may be selectively impaired. Thus, the level of analysis and the factors emphasized often differs among studies. Some of the differences between left and right hand performance in normals which have been attributed to hemispheric asymmetry also may be due to differential spatial compatibility of the stimulus and response (Guiard, 1984; Klapp et al., 1979; Proctor & Reeves, 1985) and differential practice between hands.

The present study was designed to address some of these issues. The purpose of Experiment 1 was to determine if the same left hand advantage could be found in normals on a non-ballistic aiming movement as has been found on ballistic aiming (Guiard, et al., 1983). If the left hand advantage sustains, this would suggest the right hemisphere also plays a role in the processing of sensory-dependent or nonballistic movements. The mechanism for right hemisphere control will not be directly specified in this study except to differentiate whether programming or execution are more asymmetrically controlled. The purpose of Experiment 2 was to examine arm performance ipsilateral to lesion on this same task in right and left hemisphere damaged patients to more directly assess the differential roles of the hemispheres in controlling these movements. The relationship of lesion size and location to performance also was examined, and dominant hand effects were controlled.

EXPERIMENT 1

Before developing predictions about the roles of the hemispheres in motor control, it is important to distinguish between measures associated with programming versus execution in the context of a nonballistic simple aiming task. RT, the interval prior to movement, is regarded as a measure of central programming time, and reflects the speed of planning a movement's direction, velocity, or amplitude. Even though nonballistic movements can be modified after the movement begins, they still require some planning and initiation which is reflected by RT (Keele, 1981; Kerr, 1978). Furthermore, although this task was designed to be largely nonballistic, it is likely to have a slight ballistic component as well (Flowers, 1975).

Movement time (MT) is the measure of program execution speed as well as the time it takes to monitor the response and make corrections. Constant error (CE) is a measure of the error in hitting the target, while variable error (VE) reflects the variability of performance regardless of accuracy; for this task both measures likely reflect self-monitoring and execution accuracy as visual input is not restricted and the movements are long duration. If the movements were ballistic, CE and VE could reflect programming accuracy independent of sensory feedback.

With this analysis of nonballistic movements in mind, we predict that if the right hemisphere is more important in preparing, programming, and executing nonballistic aiming movements, the left arm of normal right handers should have lower RT, MT, VE, and CE than the right arm. If the right hemisphere is more responsible for programming than executing the nonballistic movement, one might expect lower RTs for the left arm, but no left–right arm differences for MT, VE, or CE which are more related to execution in a nonballistic movement.

On the assumption that movement performed in the left hemispace should be performed more efficiently by the right hemisphere than movements in the right hemispace (Heilman & Van Den Abell, 1979; Heilman et al., 1985), the left arm superiority should be exaggerated in the left hemispace. The model assumes that the contralateral pathways are prepotent in controlling motor output and the right hemisphere plays a special role in processing nonballistic aiming movements in both hemispaces, but especially in the contralateral left hemispace. If the relationship between arm and hemispace is simple, left arm/left hemispace performance should be better than right arm/right hemispace performance. Performance in the left arm/right hemispace and right arm/left hemispace conditions should be relatively equal and between the left arm/left hemispace and right arm/right hemispace conditions because the mixed conditions involve either less efficient processing of right hemispace information or interhemispheric collaboration.

Contrasted with the predictions from the above model are two other models. One emphasizes the effect of crossed versus uncrossed visual input and output pathways without mention of a special role for the right hemisphere. This model predicts shorter reaction times when projecting visual input to the hemisphere which controls the motor output (e.g., right visual field/right hand) versus projecting the visual input to the opposite hemisphere (e.g., left visual field/right hand) (Berlucchi et al., 1971; Poffenberger, 1912). The other model focuses on the importance of environmental–anatomical compatibility on decision processes (Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977; Klapp et al., 1979). The first model is not directly applicable to the present study because visual input was restricted to hemispace, but not necessarily to specific visual fields. However, the second model predicts stimuli presented in the hemispace

FIG. 1. Illustration of the apparatus.

compatible with the responding arm (right hemispace/right arm or left hemispace/left arm) should be processed more efficiently than stimuli presented in the hemispace opposite to the responding arm.

Method

Subjects. Twenty right-handed normal males were tested at the Albuquerque Veterans Administration Medical Center. The right and left arm groups were composed of 10 subjects each, who had performed the task with their right or left arm. Subjects in the right arm group had a mean age of 63.9 (SD = 5.7) and an average of 10.8 (SD = 2.9) years of education. Subjects in the left arm group had a mean age of 58.9 (SD = 5.5) and an average of 12.5 (SD = 4.1) years of education. There were no reliable differences between groups in age or education.

Apparatus and procedure. Figure 1 illustrates the apparatus used in the arm reaching task. Stimuli were projected on a HI-PAD digitizer interfaced with an Apple II Plus microcomputer that allowed for a 0.125-mm resolution and sampled points every 10 msec during movement. Subjects could see the digitizing tablet on a video monitor, but direct view was blocked by use of a chin rest. The targets consisted of wide (diameter = 30 mm) or narrow (diameter = 5 mm) circles which were connected to the starting point by two parallel lines that were 150 mm long and 30 or 5 mm apart. These stimuli were chosen rather than the more traditional target circle alone to maximize the necessity of monitoring the ongoing response since the subject's instructions were to stay within the parallel lines. Stimuli were projected to the right or left hemispace (60° and 120° from horizontal).

The subject's arm and hand were fit in a cloth mitten, and an orthoplast splint allowed only elbow and shoulder movement. The digitizer stylus was fixed to the splint and a small light-emitting diode (LED) was fixed on the point of the stylus allowing the subject to continuously monitor his arm and hand position during movement in the visual condition. In the nonvisual condition, the LED was turned off which prevented subjects from visually monitoring their hand and arm position during movement. In addition, during the time interval after the stylus was centered but before the subject was cued to respond, the screen was blanked in both conditions.

At the beginning of each trial, subjects were presented with a starting point stimulus (diameter = 3 mm) on the monitor and were instructed to move their arm so that the stylus was on top of the starting point. Once the subject was correctly positioned on the starting point, the trial was initiated by "blanking" the video monitor for a time interval of 1 to 2 sec. Immediately following this interval, the target stimulus was presented, and subjects were instructed to move as quickly and accurately as they could through the parallel lines to the target circle. When the target stimulus was presented, the LED remained on in the visual condition and was turned off in the nonvisual condition thus cueing subjects during the RT interval as to whether they would receive visual feedback during movement.

There were eight different stimuli consisting of all combinations of feedback conditions (visual and nonvisual), target width (wide and narrow), and hemispace (left and right). Stimuli were presented in randomized blocks of trials such that each stimulus was presented twice within each block of 16 trials for a total of 80 trials. Each control group was tested first on the hand used in this analysis. Prior to experimental trials, one practice trial was given on each of the eight stimuli.

Measurements. A total of four measurements were calculated on each trial: RT, MT, CE, and VE. RT was the interval from when the target stimulus appeared on the monitor to when the subject had moved 2.5 mm. MT began at the end of the RT interval and ended once the subject had held the digitizer stylus still for 1 sec. In calculating MT, this last second was not included. Error measures were all relative to target size. CE was the distance (mm) from the last point sampled during MT to the closest edge of the stimulus target circle. VE was the square root of the variance (standard deviation) of CE.

Results

The RT results were generally consistent with more efficient programming of nonballistic aiming movements by the right hemisphere. It took significantly longer to program right arm movements ($\bar{X}$ = 807 msec) than left arm movements ($\bar{X}$ = 652 msec) [$F(1, 18) = 5.47, p < .05$]. However, Fig. 2 shows that while right arm movements in the right hemispace took longer to program than left arm movements in the left hemispace [$F(1, 18) = 7.09, p < .05$] and there was no reliable difference in RT between right and left arm movements in the contralateral hemispace, the within-arm effects of hemispace on RT were different between arms. Specifically, hemispace and arm interacted [$F(1, 18) = 4.60, p < .05$] such that there was no hemispace effect for left arm movements, but right arm movements in the right hemispace took longer to program ($\bar{X}$ = 833 msec) than those in the left hemispace ($\bar{X}$ = 781 msec) [$F(1, 9) = 5.67, p < .05$]. Additionally, for movements in the left hemispace, there was no difference in RT between arms whereas for those in the right hemispace, RT was longer for movements with the right arm ($\bar{X}$ = 833 msec) than the left arm ($\bar{X}$ = 647 msec) [$F(1, 18) = 6.57, p < .05$]. While RTs were longer for movements to narrow targets ($\bar{X}$ = 770 msec) than wide targets ($\bar{X}$ = 689 msec) [$F(1, 18) = 36.94, p < .001$], Fig. 2 also shows that RT

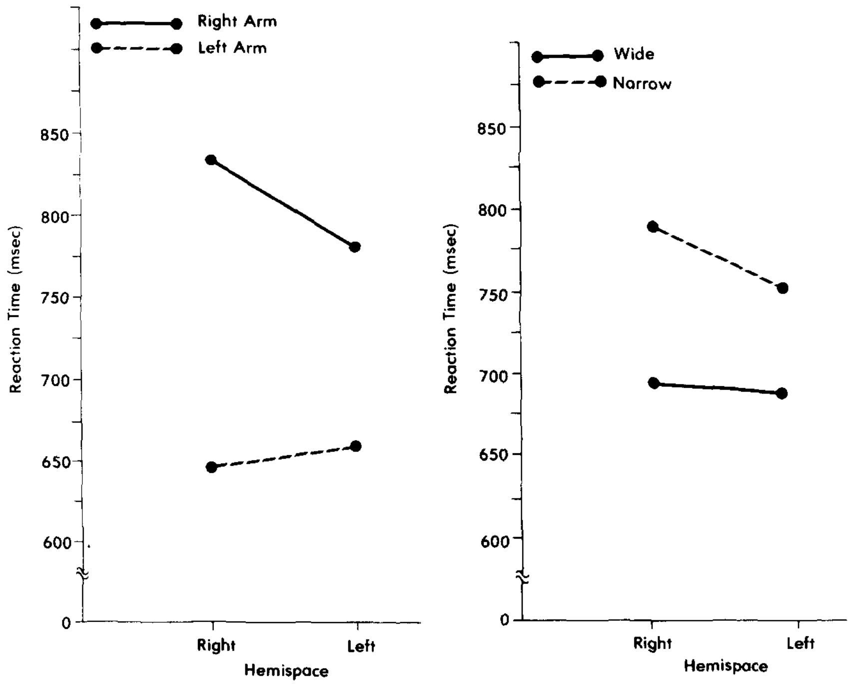

FIG. 2. Reaction times (RT) to stimuli presented in the right and left hemispace. (The left graph depicts these RTs as a function of arm, and the right graph depicts these RTs as a function of target width. Standard errors of the mean ranged between 36 to 41 msec for the right arm, 51 to 60 msec for the left arm, 32 to 38 msec for wide targets, and 36 to 46 msec for narrow targets.)

varied with target width and hemispace $F(1, 18) = 5.12$, $p < .05$], indicating that programming time increases between wide and narrow targets were 35 msec greater for movements in the right $F(1, 18) = 30.74$, $p < .001$] versus left hemispace [$F(1, 18) = 28.37$, $p < .001$]. As for the effects of visual feedback, RTs were 33 msec faster with visual guidance ($\overline{X} = 713$ msec) than without visual guidance ($\overline{X} = 746$ sec), but visual guidance did not interact with target width, arm, or hemispace.

Turning to performance variables, MT, CE, and VE were not as clearly related to the predicted right hemisphere role. MTs were clearly in the nonballistic range for both arms ($\overline{X} = 1882$ msec). However, MT did not differ between arms and was not related to hemispace or visual guidance. MTs were longer to narrow ($\overline{X} = 2055$ msec) than wide targets ($\overline{X} = 1709$ msec) [$F(1, 18) = 14.39$, $p < .001$], and target width interacted with visual guidance [$F(1, 18) = 13.48$, $p < .01$] such that execution time was especially long to narrow targets with visual guidance. Visual guidance did not reliably affect MT to wide targets, but MT to narrow targets was significantly longer with visual guidance [$F(1, 19) = 4.87$, $p < .05$]. This latter finding is consistent with the greater utilization of visual feedback during movements to narrow versus wide targets.

Contrary to previous results (Guiard et al., 1983), CE had no simple relationship with arm or hemispace. Not surprisingly, CE was considerably lower with visual guidance ($\bar{X} = 1.8$ mm) than without visual guidance ($\bar{X} = 22.9$ mm) [$F(1, 18) = 59.76$, $p < .001$] and was lower for movements to wide ($\bar{X} = 9.1$ mm) than to narrow targets ($\bar{X} = 15.6$ mm) [$F(1, 18) = 14.39$, $p < .001$]. CE also varied with target width and visual guidance [$F(1, 18) = 31.25$, $p < .001$] such that accuracy decreased with increased precision, particularly for movements without visual guidance. CE also varied with precision, arm, and hemispace [$F(1, 18) = 14.23$, $p < .001$] indicating that for movements with the left arm, CE increased with precision more in the left than right hemispace. In contrast, for movements with the right hand, CE increased with precision slightly more in the right than left hemispace. Otherwise, there were no differences between arms in CE.

VE did not differ between arms and was not related to precision or hemispace in any simple way. Although VE was lower with visual guidance ($\bar{X} = 1.4$ mm) than in the absence of visual guidance ($\bar{X} = 11.5$ mm), visual feedback interacted with precision and hemispace [$F(1, 18) = 5.44$, $p < .05$], such that for movements in the right hemispace with visual guidance and for those in the left hemispace without visual guidance, the variance in accuracy increased with increasing precision requirements. Otherwise, there was no effect of precision on VE for movements in the right hemispace without visual guidance or for those in the left hemispace with visual guidance.

Discussion

There were several main findings pertaining to the hypothesized hemisphere effects. First, as predicted, it took longer to program a right than a left arm movement which was consistent with the right hemisphere's dominance in the planning of nonballistic arm movements in a spatial context. However, there was no reliable difference in programming time between right and left arms for movements in the left hemispace although there was a nonsignificant trend for RTs to be faster for the left arm. In addition, movements with the right arm in the right hemispace took longer to program relative to all other arm/hemispace combinations. Spatial compatibility between stimulus and response unit cannot explain our results because our within-hand findings suggested a bias in favor of programming movements in the left hemispace for the right and left arm.

Our findings are more consistent with an explanation of the right hemisphere's special role in programming rather than executing nonballistic aiming movements. This could be due to the right hemisphere's role in spatial skills since the movements were performed in a spatial context; but if that were the case, we might expect that the left arm/left hemispace effects would be present for the performance measures (MT, CE, VE). Other explanations would focus upon the hypothesized role of the right hemisphere in attention, intention, or general preparation to respond (Heilman & Van Den Abell, 1979; Heilman et al., 1985), or perhaps other aspects of programming specific to closed loop aiming movements. The present experiment cannot differentiate these possibilities.

Our second main finding that RTs were particularly long to narrow targets in the right hemispace also is consistent with these hypotheses. These results suggest that if information is biased for right hemisphere processing (left hemispace or left arm), the subject's performance is more efficiently programmed. However, if there is no such bias programming speed suffers.

The findings from the performance measures do not suggest that the right hemisphere is more important in executing the motor program, or in monitoring and correcting movement. MT, CE, and VE did not differ as a simple function of arm or hemispace. In addition, for all performance measures, arm and hemispace did not vary in any consistent way with target width or visual guidance; given previous results (Guiard et al., 1983), we expected that any manipulation to increase the ballistic component of the movement (i.e., wide target, no visual guidance) would increase the right hemisphere's role. However, because all MTs were very long and clearly longer than the minimum times necessary to transmit sensory information (Keele, 1981), target width and visual guidance may not have exerted the anticipated effect on execution measures.

As a final comment, our RTs were long relative to other comparable studies which have reported RTs in the range of approximately 250 to 350 msec. This can be attributed to several characteristics of our procedure. The warning signal consisted of blanking the monitor 1 to 2 sec prior to stimulus onset, but the warning signal also indicated that the stylus was centered, so subjects would need to apprehend this information as well as prepare for the stimulus. Subjects may not have had sufficient time to prepare for the stimulus which would result in longer RTs and perhaps, increase the variability in RT as well. Additional reasons for our long RTs are that all stimuli were randomly presented without cues, and our subject population was older than in most studies.

EXPERIMENT 2

In order to more directly assess the role of the hemispheres in nonballistic movements, responses ipsilateral to lesion were examined. Right cerebrovascular (CVA) patients were compared to normal subjects performing with their right arm, and left CVA patients were compared to normal subjects who performed the task with their left arm. Direct contrasts were done between these two groups because they do not confound arm and hemisphere effects. RT for the arm contralateral to lesion was examined in patients who were not hemiparetic.

On the basis of the findings in normals from Experiment 1, it was predicted that RT which is reflective of central programming efficiency should be more impaired after right than left hemisphere damage. Even though Experiment 1 demonstrated no hand differences for execution, this could be due to ceiling effects in normals; execution differences may be more apparent in brain damaged patients. If the right hemisphere is important for the execution of these movements, MT, CE, and VE also should be more impaired after right than left hemisphere damage.

Method

Subjects. All subjects were right-handed males and were tested at the Albuquerque Veterans Administration Medical Center. The subject groups included the 20 normals from Experiment 1, 10 patients with CVAs of the right hemisphere and 10 patients with CVAs of the left hemisphere. The same data from normals that was reported in Experiment 1 was used for the control conditions. The CVA patients used the hand ipsilateral to lesion except in nonhemiparetic patients who were tested with both limbs. Patients were eliminated from the study if they evidenced nonneurological disease which could cause motor disability (e.g., arthritis, fractures, etc.), neurological disease other than stroke, or bilateral hemispheric damage based on CT scans or neurological exam. Subjects also were eliminated if they had psychiatric hospitalizations or were chronic alcoholics.

Age and education levels were matched between groups performing with the same hand (i.e., right normals and right CVAs; left normals and left CVAs). The average age of right CVAs was 67.6 years (SD = 7.3), and they had a mean educational level of 11.1 years (SD eq 3.4). The left CVAs had an average age of 60.0 years (SD = 5.8) and a mean educational level of 13.1 years (SD = 3.7). The right CVA group was significantly older than the left CVA group, [$F(1, 18) = 6.29, p < .05$]. Although CVA groups did not differ in mean age from their respective control groups, age was covaried in all analyses to control for its relationship to RT, MT, CE, and VE. Means in all figures were not age-corrected since the adjusted means were very similar to observed means. There was no difference between patient groups in the average number of months post-CVA; 66.1 months (SD = 43.5) for right CVAs and 69.0 months (SD = 36.0) for left CVAs.

Table 1 provides a description of the language and sensory data. The left CVA group performed significantly worse than all other groups on auditory comprehension using Parts I, III, and V of the Token Test (DeRenzi & Vignolo, 1962) [$F(1, 35) = 8.1, p < .01$] or Part V alone [$F(1, 35) = 7.4, p < .01$]. They also performed worse on fluency ratings [$F(1, 35) = 11.3, p < .01$] and repetition of low probability sentences [$F(1, 35) = 6.2, p < .01$] from the Boston Diagnostic Examination of Aphasia (Goodglass & Kaplan, 1972). Ipsilateral two-point discrimination of the forearm was significantly impaired in both stroke groups relative to the controls, [$F(1, 35) = 7.59, p < .01$]. While no other somatosensory impairments were found, an examination of Table 1 shows that there was greater variability in finger position sense for both stroke groups relative to the control groups. Ipsilateral finger tapping and grip strength were not impaired for the stroke groups relative to the controls, but pegboard performance was impaired in both stroke groups [$F(1, 35) = 6.15, p < .05$]. These results are in agreement with previous data (Haaland & Delaney, 1981).

As for the incidence of hemiplegia, four right CVA patients and five left CVA patients were classified as hemiplegic with hemiplegia defined as contralateral grip strength equal to 0 and ipsilateral grip strength greater than 0. Ipsilateral grip strength did not differ

TABLE 1

MEANS (STANDARD DEVIATIONS) FOR LANGUAGE AND SENSORY DATA

	Right control	Left control	Right CVA	Left CVA
Auditory comprehension				
Token test (errors)				
Parts I, III, V (41)[a]	3.5 (3.2)	3.1 (2.7)	5.1 (5.0)	17.4 (11.9)
	3.1)			
Part V (21)[a]	(2.7)	3.0 (2.4)	4.6 (4.2)	12.2 (6.6)
Language fluency (BDEA)				
Speech rating (7)[b]	6.9 (.1)	7.0 (.1)	6.9 (.2)	4.9 (1.9)
Repetition (low probability) (8)[b]	7.3 (.9)	7.1 (1.7)	7.1 (1.0)	4.9 (2.5)
Ipsilateral somatosensory				
Two-point discrimination (cm)				
Forearm	2.9 (.6)	3.6 (1.7)	5.1 (1.6)	4.0 (1.5)
Finger	.4 (.2)	.4 (.1)	.4 (.2)	.4 (.1)
Position sense (% errors)				
Forearm	0	1.1 (2.4)	0	0
Finger	2.5 (3.1)	2.0 (4.4)	4.9 (8.8)	4.4 (7.1)
Ipsilateral motor[c]				
Grip strength	49.4 (10.1)	51.0 (9.3)	41.7 (8.7)	49.0 (6.8)
Finger tapping	46.4 (5.8)	46.9 (7.6)	38.7 (8.4)	43.9 (4.2)
Pegboard	35.3 (18.4)	43.4 (18.9)	.9 (53.1)	30.2 (17.6)

Note. Occasionally, data points are based on fewer than 10 left or 10 right CVA patients due to missing data on one or two subjects.

[a] Number of errors possible.

[b] Best possible score: low score indicates poorer performance.

[c] Scores are T scores, based on normal population from Madison, WI. Mean of this distribution = 50; standard deviation = 10.

significantly between hemiplegic and nonhemiplegic patients [$F(1, 17) < 1$, $p > .05$] or between right and left CVA groups [$F(1, 17) = 4.3$, $p > .06$]. One right CVA patient and four left CVA patients were classified as limb apraxic (Haaland & Flaherty, 1984). Two right CVA patients and one left CVA patient had at least a partial visual field cut. One right CVA patient and one left CVA patient demonstrated visual extinction on bilateral simultaneous stimulation, but neglect was not assessed in other ways.

CT-scan quantification. CT scans were available on 7 of the 10 left CVA patients and 9 of 10 right CVA patients. CT scan parameters were quantified in order to obtain measures of lesion size and location (anterior vs. posterior) using previously published procedures (Haaland et al., 1988). Lesion location was quantified in terms of anterior and posterior lesion volume, and distance of the lesion from frontal and occipital poles. The anterior position of the lesion was expressed as the distance from the most anterior end of the lesion to the frontal pole, and the posterior distance was expressed as the distance from the most posterior end of the lesion to the occipital pole. In addition, the location of lesion in terms of specific anatomical areas (e.g., frontal and parietal lobes, etc.) also was tabulated.

Procedure and design. The same apparatus and procedure as described in Experiment 1 was used for Experiment 2. The design of the study also contained the same within factors as in Experiment 1 (i.e., hemispace, target width, and feedback condition). Between-group comparisons consisted of comparisons between left normals and left CVAs, and

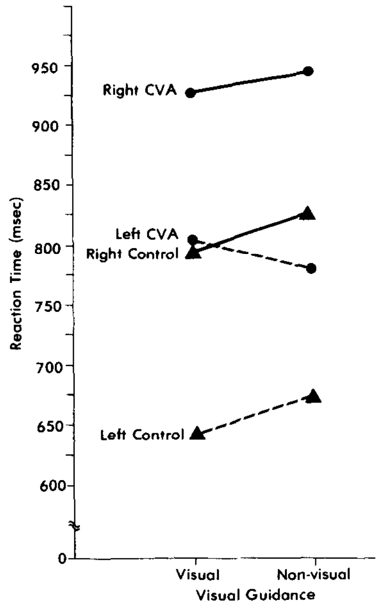

FIG. 3. Reaction times (RTs) as a function of visual guidance condition for CVA patients and control subjects. (Standard errors of the mean ranged between 35 to 58 msec for control subjects and 64 to 77 msec for CVA patients.)

right normals and right CVAs, in order to control for differences between hands in the execution of simple aiming movements.

Results

The regression analysis of the covariate showed that subjects' age generally was not related to the dependent measures except for the analyses of MT comparing right CVAs and their control group. In this analysis, age was positively related to MT [$F(1, 17) = 7.67$] accounting for 34% of the variance.

Figure 3 suggests that there were RT differences between each CVA group and their respective control. While the difference between all CVA patients and all control subjects approached signficance [$F(1, 35) = 3.60$, $p < .06$], there were no reliable RT differences between right CVAs ($\bar{X}$ = 933 msec) and their control group ($\bar{X}$ = 807 msec) or left CVAs ($\bar{X}$ = 786 msec) and their control group ($\bar{X}$ = 652 msec). This is a surprising finding especially for the right CVA group given the results from Experiment 1. However, there was greater variability in RTs for right CVAs in comparison to control subjects which may account for these negative findings. While the variance in RTs for left CVAs was larger (SD = 214) than for their control group (SD = 173), right CVAs showed almost twice as much variance in RTs (SD = 221) than their controls (SD =

117). Another potential explanation for the RT findings is that the contralateral pathway is more prepotent than the ipsilateral pathway in demonstrating hemispheric function. In a small number of subjects who were not hemiparetic (six right CVAs and five left CVAs), RTs of the arm contralateral to lesion were examined. Despite the fact that the nonhemiparetic right CVAs were less impaired in RT than the entire right CVA group and the nonhemiparetic left CVA group was equally as impaired in RT as the entire left CVA group, nonhemiparetic right CVAs had slower RTs in their contralateral arm (by 168 msec) relative to controls using their left arm [$T(14) = 1.83$, $p < .05$], and the left CVA group's contralateral performance was similar to the right controls. This suggests that right CVAs show reliable deficits in programming nonballistic movements in the contralateral but not ipsilateral limb.

Figure 3 also shows that visual guidance differentially affected RTs only for the left CVAs in comparison to their control subjects. Specifically, RT varied with group and visual guidance [$F(1, 18) = 8.88$, $p < .01$] such that while there were no reliable differences in RT between left CVAs and their controls, advance knowledge that visual guidance would be available decreased RT for the control group [$F(1, 9) = 10.10$, $p < .01$] but not the left CVA group. This finding suggests that the left hemisphere plays some role in planning movements although the exact nature of these programming processes is not clear.

As for performance measures, left CVAs were not impaired in MT ($\bar{X} = 1987$ msec), CE ($\bar{X} = 15.2$ mm), or VE ($\bar{X} = 7.1$ mm), relative to their control group ($\bar{X} = 1498$ msec, $\bar{X} = 11.0$ mm, and $\bar{X} = 6.3$ mm, respectively) which was consistent with Experiment 1 and the right hemisphere hypothesis. There also were no reliable differences in MT between right CVA patients ($\bar{X} = 2860$ msec) and their controls ($\bar{X} = 2266$ msec); however, both CE and VE varied differentially with group. Figure 4 shows that CE varied with group and target width [$F(1, 18) = 4.78$, $p < .01$] such that right CVA patients were less accurate than control subjects only with narrow targets [$F(1, 18) = 8.57$, $p < .01$]. This effect was not significant for the left CVA group. For VE, group interacted with target width [$F(1, 18) = 5.33$, $p < .05$] showing that while there were no differences in VE between right CVAs ($\bar{X} = 8.9$ mm) and their controls ($\bar{X} = 6.6$ mm), the variability in error increased with precision when visual guidance was available, only for right CVAs [$F(1.9) = 18.98$, $p < .01$]. These findings support a role for the right hemisphere in the execution of nonballistic movements.

CT-scan analyses. It is possible that the differential pattern of findings for left and right CVA patients could be explained by differences between these groups in lesion size and/or lesion location (i.e., anterior vs. posterior). Therefore, CVA groups were compared on several lesion volume and location parameters. Figure 5 presents a composite diagram of the

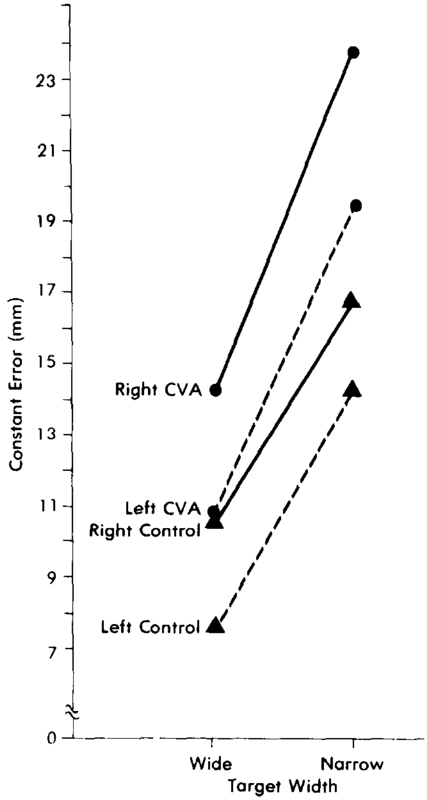

FIG. 4. Constant error (CE) as a function of target width for CVA patients and control subjects. (Standard errors of the mean ranged between 1.6 to 2.3 mm for control subjects and 1.8 to 2.7 mm for CVA patients.)

CT scans for all patients. Lesions from each patient were superimposed so that increased density reflects lesion overlap. Table 2 presents the lesion volume and distance measurements for each CVA group. This table suggests that both CVA groups were equivalent in total lesion volume, which was supported by the statistical analyses. While anterior and posterior lesion volumes did not differ significantly between groups, the lesions of the right CVA group were decidedly more posterior than anterior. The supporting statistical analyses showed that 33% of the variance in the difference between anterior and posterior lesion volume was accounted for by CVA group [$F(1, 14) = 6.90, p < .05$].

The lesion distance measures which reflect the extent to which lesions are located near the frontal or occipital poles are consistent with volume measures. Lesions were more anterior for left than right hemisphere damaged patients, and lesions were more posterior for right than left

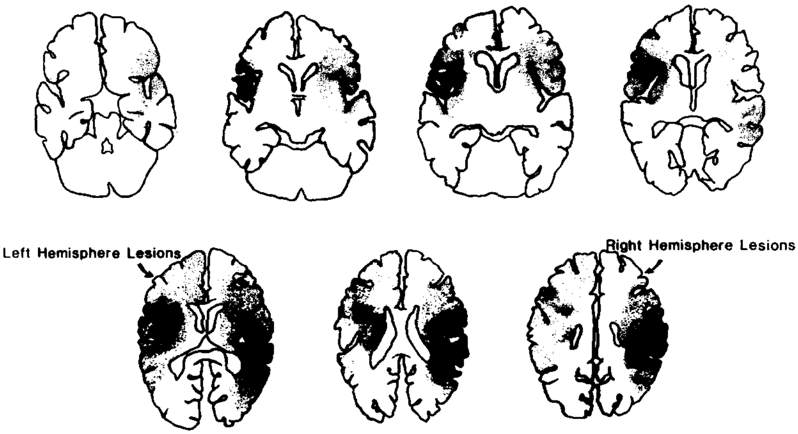

FIG. 5. Superimposed CT-scan abnormalities for 9 of the 10 right hemisphere damaged patients and 7 of the 10 left hemisphere damaged patients. (The left hemisphere group is shown on the left and the right hemisphere group is shown on the right.)

hemisphere damaged patients. In fact, an examination of the ranges shows that to a large extent the distributions of frontal distances between CVA groups was not overlapping. This also is the case for the distributions of posterior distances, but to a lesser degree. The supporting statistical

TABLE 2
MEANS (STANDARD ERRORS) AND RANGES OF LESION VOLUME AND DISTANCE MEASURES FROM PATIENTS WITH UNILATERAL CORTICAL LESIONS[a]

	Right CVAs		Left CVAs	
	Mean (*SE*)	Range	Mean (*SE*)	Range
Volume measures[b]				
Total lesion volume	.060 (.025)	.003–.175	.061 (.021)	.008–.172
Anterior lesion volume	.033 (.016)	.000–.109	.050 (.014)	.008–.108
Posterior lesion volume	.028 (.010)	.000–.085	.001 (.009)	.000–.064
Difference: Anterior–posterior volume	.005 (.008)	.002–.056	.049 (.010)	.008–.077
Distance measures[c]				
Frontal distance	.391 (.048)	.540–.157	.158 (.036)	.006–.271
Posterior distance	.327 (.042)	.492–.062	.474 (0.47)	.278–.660

[a] Data points are based on CT scans from nine right CVAs and seven left CVAs.

[b] All volume measures are proportional to the total brain volume in order to correct for differences in CT scan size. As for the difference between anterior and posterior lesion volumes, positive numbers reflect larger anterior volumes relative to posterior volumes.

[c] All distance measures are proportional to the total distance from the frontal to the occipital pole. A smaller proportion for the frontal and posterior distance reflects that the lesion is located closer to the frontal or occipital pole, respectively.

TABLE 3

SUMMARY OF AREA DAMAGED FROM PATIENTS WITH UNILATERAL CORTICAL LESIONS[a]

	Right CVAs	Left CVAs
Lesion location	Frequency (Percentage)	Frequency (Percentage)
Frontal	3 (33%)	6 (86%)
Temporal	5 (56%)	4 (57%)
Parietal	8 (89%)	3 (43%)
Occipital	1 (11%)	0
Subcortical	3 (33%)	4 (57%)
Insula	1 (11%)	0

[a] Data are based on scans from nine right CVAs and seven left CVAs.

analyses showed that 49% of the variance in frontal distance and 27% of the variance in posterior distance was explained by CVA group [$F(1, 14) = 13.71$, $p < .01$] and [$F(1, 14) = 5.31$, $p < .05$], respectively.

This anterior–posterior difference was further supported when CT results were tabulated by area of damage. This can be seen in Table 3 which shows the greater incidence of frontal involvement for the left CVAs and the greater incidence of parietal involvement for the right CVAs. Similar lesion location differences also were present when the patients without hemiparesis were examined. These results emphasize how intrahemispheric lesion location information can qualify interpretations of interhemispheric effects.

As for the relationship between the CT parameters and performance, post hoc Spearman Rank Order correlations using all CVA patients with CT data showed that more posteriorly located lesions were associated with significantly longer RTs ($r = .49$) and larger posterior lesion volumes were related to greater variability in errors ($r = .52$). No other lesion volume or location parameter correlated significantly with performance. Due to small sample sizes, these correlations were not performed separately for each CVA group to see whether a differential pattern or relationships might exist between CT parameters and performance.

Discussion

Although RTs in the arm ipsilateral to lesion were not longer in right vs. left hemisphere CVA patients, RTs in the contralateral limb were longer in the right but not left CVA group. Whether this effect reflects inter- or intrahemispheric differences in function is not clear since the two groups differ in both. There was a tendency, though not statistically significant, for both CVA groups to show longer RTs with the ipsilateral arm than their respective control groups, similar to one other study (Benton & Joynt, 1958). While there were no differences in RT between left CVA patients and their control group, the left CVA group's planning of a movement was not improved by knowing visual feedback would be available during the movement. In contrast, the right CVA group's RT decreased if visual feedback was going to be available but frequently the visual feedback didn't improve their performance.

For performance measures, left CVA patients were not impaired relative to controls in MT, CE, or VE. However, right CVA patients were sometimes less accurate than control subjects particularly for movements to narrow targets *with* visual guidance. These findings suggested that the right hemisphere or parietal areas may play a more important role in the programming and execution of nonballistic movements. The deficits in monitoring of movement and the utilization of visual feedback are not seen in normals probably due to ceiling effects. The left hemisphere or frontal areas may appear to be more involved in some aspects of programming but not executing ipsilateral nonballistic movements.

GENERAL DISCUSSION

The most interesting finding from Experiment 1 was that RTs in normal subjects were faster with the left than the right arm only for movements in the right hemispace. While hemispace did not influence RTs for the left arm, RTs for the right arm were affected in the predicted direction such that they were slower in the right than the left hemispace. However there were no significant differences between the two hands or the two hemispaces in either of the variables associated with execution. These findings from normal subjects were consistent with a model in which the right hemisphere plays a predominant role in the programming as opposed to the execution of these movements. The mechanism of the control is unclear and could be due to stronger right hemisphere control of attentional or intentional functions, or could be more specific to the requirements of programming nonballistic as opposed to ballistic aiming movements. The only finding from Experiment 1 that was inconsistent with these interpretations was an absence of a reliable arm effect for movements in the left hemispace. An alternative explanation for these results is that the right hemisphere's role in controlling these movements could be associated with the spatial nature of the simple aiming task. However, as there were no significant differences between the right and left arm of normals for execution variables, the spatial hypothesis seems less likely although our task may not have pressed spatial processing. Given the fact that others (Guiard, et al., 1983) have demonstrated similar effects for ballistic movements, our results are not likely to be specific to the programming requirements of nonballistic movements although these two types of movements must be directly compared in the same experiment to determine if right hemisphere control is different for the two movement types.

None of the hypotheses discussed in this paper can explain why in normal subjects RTs were faster in the left than right hemispace particularly for narrow targets. This is an interesting finding because it implies that when the degree of a movement's dependence on sensory feedback is manipulated, the programming of a movement which is more dependent on sensory feedback (i.e., narrow target) takes longer, especially in the right hemispace. This suggests the possibility that the right hemisphere's bias for programming left hemispace information more quickly is enhanced by the extent to which the movement relies on the utilization of sensory feedback.

The findings from Experiment 2 supported the role of the right hemisphere or parietal lobe in the programming of contralateral but not ipsilateral closed loop movements. RT with the ipsilateral arm was not differentially slower in the right CVA group, even in the left hemispace which would have been predicted if the right hemisphere controls the cognitive aspects of this task. This is inconsistent with previous results (Heilman et al., 1985) which compared right hemisphere patients with neglect and left hemisphere patients without neglect. However, our group of right hemisphere patients not selected for neglect but with greater parietal damage showed slower RTs in the contralateral hand. So the right hemisphere or parietal lobe may play a role in programming movements in the contralateral limb while patients with neglect show slower RTs even in the ipsilateral limb (Heilman et al., 1985). Unfortunately, neglect data were not available in our sample.

The left CVA group was slightly impaired in their ability to utilize advance information about the availability of visual guidance during movement which may suggest that the left hemisphere plays some role in preplanning even closed loop movements. However, because most aiming movements comprise an initial ballistic component followed by corrective nonballistic movements to hit the target (Flowers, 1975, 1976), the RT findings for the left CVA group could also be reflective of the left hemisphere's prepotence for programming the ballistic component of movements (Haaland et al., 1987). As left CVA patients clearly had more anterior lesions, the RT findings also may be attributed to intrahemispheric lesion location which is consistent with a previous study that suggested either the left hemisphere or anterior areas of each hemisphere may be prepotent in programming ballistic movements (Haaland et al., 1987).

Experiment 2 also showed that the right CVA group had reliably larger CEs than their control group (on the narrow target only), and the variability in accuracy was greater in the narrow target condition when visual feedback was present. No such execution deficits were found for the left CVA group. These results offered more direct support for the dominant role of the right hemisphere in the execution of nonballistic simple movements. Again, it is not clear whether the initial, programmed component or the later sensory-dependent component of nonballistic movements were more impaired, although Guiard et al.'s (1983) findings would seem to suggest the former whereas another study using a different task has shown no evidence for the right hemisphere's specialization in programming ballistic movements (Haaland et al., 1987). Unfortunately, our measurements did not allow for the separation of these two components of movement. Nonetheless, either interpretation of these findings also could be attributed to the greater incidence of posterior lesions in the right hemisphere group particularly since greater posterior lesion volumes were associated with greater VE.

In conclusion, the present study supports the idea that the right hemisphere plays a special role in programming closed loop movements of the contralateral but not ipsilateral hand and in execution of the ipsilateral limb. Any discrepancies between the two experiments may be due to several factors including the large variance in RT for the right CVA group, ceiling effects on execution parameters for normal subjects, and differences in intrahemispheric lesion location among stroke patients. Because ballistic movements were not directly examined in the present study, we cannot comment on the possibility that the right hemisphere controls both ballistic as well as nonballistic movements, at least in the context of a discrete aiming task with a spatial component. Similarly, the different pattern of RT findings for left and right CVA groups may be reflective of a selective impairment in different mechanisms which could not be directly specified by the present study. We are currently examining ballistic and non-ballistic components of simple aiming in order to better understand the underlying mechanism, and to determine if these movements are differentially controlled by different hemispheres and/or different locations within the same hemisphere.

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