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RESEARCH ARTICLES

Luc Tremblay · Timothy N. Welsh · Digby Elliott

Between-trial inhibition and facilitation in goal-directed aiming: manual and spatial asymmetries

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Abstract Three experiments were conducted with right-handed participants to examine between-trial inhibition and facilitation effects in goal-directed aiming. Participants were required to execute rapid left-hand or right-hand aiming movements upon illumination of a target light in left or right space. Thus, from trial to trial, participants executed movements to either the same target location or a different target location with the either same hand or the other hand. Our reaction time results indicated that participants were particularly slow in initiating their movements when they were required to return to the same target location with the other hand. This was especially the case when the right hand was required to move to a target just occupied by the left hand. For both reaction time and movement time the right hand but not the left hand exhibited an advantage when it was required to perform the same movement two times in a row. Taken together these results suggest that inhibition of return, in a target-target paradigm, is more associated with the particular spatial location of the target than the organization of a specific movement to that location. Moreover, the between-trial facilitation observed for the right hand may reflect the ability of the left cerebral hemisphere to maintain an already parameterized motor program over a short intertrial interval.

Keywords Movement preparation · Asymmetries · Attention · Aiming · Limb control

L. Tremblay · T. N. Welsh
University of Toronto,
Toronto, Canada

T. N. Welsh · D. Elliott (✉)
McMaster University,
Hamilton, ON, L8S 4K1, Canada
e-mail: elliott@mcmaster.ca
Tel.: +1-905-5259140
Fax: +1-905-5234025

Introduction

A number of researchers have demonstrated that persons take more time to respond to a repeated event than to respond to a new event even though the probability of the two events is equal (Posner and Cohen1984). For example, when a target stimulus is presented in the same location on trial N and N+1, participants take longer to respond to the target on the N+1 trial than if the target was presented in a different location (Maylor and Hockey1985; Spence et al.2000). More recent studies have shown that a portion of this inhibitory effect is tied to the location of the target and a portion to the target object itself (Tipper et al.1999a, 1999b; Weaver et al.1998).[1] From an evolutionary point of view the processes underlying this "inhibition of return" (IOR) phenomenon are thought to be functional as they impede an organism's attentional shifts to locations and/or objects that have already been responded to or investigated (Posner et al.1985). Presumably these environment- and object-centered inhibitory processes have developed to prevent perseveration and thus are useful in activities such as food gathering and hunting.

Many of the original studies designed to examine IOR used simple key-pressing tasks. That is, participants were asked to detect the presence of a single target, presented in one of a number of possible locations, by rapidly depressing a button. Of interest to motor control researchers are several more recent studies that were designed to examine inhibitory effect in the context of actual aiming/reaching movements to targets (e.g., Briand et al.2000; Welsh and Elliott, 2004b). In one such study Howard et al. (1999) reported that a noninformative cue delayed the subsequent initiation of a reaching movement to a target at the same location when the interval between

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[1] Here inhibition and facilitation effects refer to relatively faster or slower reaction or movement times for responses to target locations. Although these temporal effects are likely the result of different patterns of neural events, we draw no conclusions about the specific neural events that lead to the behavioral differences; for a review of the possible neural coding of such effects in the oculomotor system of nonhuman primates see Fecteau and Munoz (2003).

the cue and the target was 200 ms or 600 ms. Interestingly, following the 200 ms cue-target interval the movement trajectories to the target were also affected when the location of the cue and target were different. Presumably, under these conditions, the cue and the target both activated response-based representations and the performer did not have sufficient time to establish an inhibitory field against the response to the cue (Posner et al. 1985). Results such as these, in consort with findings suggesting that these inhibitory processes do not affect perceptual (i.e., temporal order) judgments, have led to the suggestion that IOR is not simply an effect caused by inhibiting attention to a location or stimulus but of the *response* to that location or stimulus (for a recent review see Klein2000).

This motor explanation of IOR is consistent with several action-based models of selective action that suggest turning one's visual attention to an object or location in space may be the same process as preparing a movement to that object/location (e.g., Rizzolatti et al.1994; Tipper et al.1992; Welsh and Elliott 2004b; Welsh et al.1999). However, the finding that there is a temporal disadvantage associated with performing the same movement two times in a row flies in the face of several studies in the motor control literature that indicate there are temporal advantages associated with repetition. For example, Rosenbaum et al. (1987) have shown that participants are faster repeating an even-numbered string of two to ten letters than an odd-numbered string when they are required to alternate loud-soft intonation on every letter. This is thought to occur because the intonation associated with a particular letter is the same from trial-to-trial in an even-numbered series and thus can be maintained over the intersequence interval. For an odd-numbered string of letters the "motor program" for producing the string of letters must be reparameterized each time to accommodate the new intonation. This type of trial-to-trial facilitation has also been shown for finger sequencing (Rosenbaum et al.1987), and reach-to-grasp movements (Rosenbaum and Jorgensen1992).

One purpose of the present research was to examine the influence of target location and movement planning on between-trial inhibition, and perhaps facilitation, processes. Participants were asked to make rapid left- or right-hand aiming movements to equally probable visual targets presented in left and right space. In some situations consecutive aiming movements were made with the same hand and on other trials the aiming movements were made with the other hand. The idea was that any IOR effect associated with strictly an attention-based mechanism related to target location should generalize across effector. Further, if inhibition is associated with the location of the target and not merely the responding effector, any facilitation effect associated with repeating a movement (e.g., returning to the same target with the same hand; see Rosenbaum et al.1987) should be reduced when performing two consecutive movements to the same target with different hands. This is because not only the limb performing the action but also the muscle group involved in the action would need to be reparameterized between trial N and trial N+1 (see Rosenbaum1980). In contrast, if both shifting attention to a location in space and planning a movement to that location are one in the same process, IOR would not be expected to generalize across effector. Given this situation, IOR effects should be greatest when repeating a specific movement (i.e., same hand to same target).

An additional purpose of this research was to examine both spatial and manual asymmetries associated with inhibition and facilitation effects. Both clinical and experimental work on cerebral specialization indicates that in most right-handers the left cerebral hemisphere has a special role to play in the organization and control of goal-directed movement. This asymmetry in function is typically reflected in a temporal advantage for the right hand in the organization and control of finger sequencing and rapid aiming movements (for a review see Elliott and Chua1996). In the present research we were interested in determining whether the right-hand system enjoys a greater advantage when repeating a just-executed movement than the left hand system. Specifically, if the temporal advantages associated with the right-hand system are the result of a better ability to specify the muscular forces required for motion (e.g., Sainburg2002), facilitation effects for the right hand may be greater than those for the left hand.

Also in the context of the laterality literature the right cerebral hemisphere (left-hand system) has been shown to play a special role in the allocation of attentional resources in three-dimensional space (e.g., Heilman1979). Moreover, for most right-handed persons the left hand enjoys a reaction time advantage over the right hand, particularly when responding to targets in left space (for a review see Carson1996). This is especially true when the aiming involves spatial uncertainty (Mieschke et al.2001). Thus of interest in the present study were any trial-to-trial inhibitory effects that are more pronounced following a left hand movement or movements in left space.

Our general approach was to have participants aim from a central home position to equally probable targets in left and right space. Consecutive movements were completed with either the same hand or the other hand. We conducted three separate experiments that varied with respect to the length of intertrial interval and how the hand for a particular trial was determined. These variations in method were introduced to ensure that any inhibition, facilitation, and/or asymmetry effects were not contingent on order or spacing variables that were not of theoretical interest. For ease of presentation the methods and results of these protocols are reported together.

Method

Participants

The study involved three separate experimental protocols that varied only with respect to trial blocking, and intertrial interval. Twelve different young adults (age range 18–30 years) participated in each of the three protocols: six men and six women in protocol 1, six men and six women in protocol 2, and four men and eight women in protocol 3. All participants were strongly right-handed (Bryden1977) and had normal or corrected to normal vision. Participants were provided a small financial compensation for their time ($10). All participants provided informed consent prior to involvement in the any of the experiments. Our research was approved by the McMaster Research Ethics Board and was therefore in accordance with the ethical standards laid down in the Declaration of Helsinki.

Apparatus and procedure

The experimental setup (see Fig. 1) involved a two-target array and a home position as well as an Optotrak 3020 system (Northern Digital) linked to a four-bank timer (Lafayette Instruments) and a Pentium Computer. In protocol 1 the targets were red light emitting diodes (LEDs) installed within a 2 cm diameter button and located 40 cm away from the home position (Y-axis) and 18 cm to the left or the right (X-axis) of a third red-green LED that served as a central fixation point. In protocols 2 and 3 the distance in the Y-axis was reduced to 30 cm to accommodate participants with a shorter reach. Although the central LED was inactive in protocols 1 and 3, in protocol 2 a stimulus was presented at the central location that instructed the participant as to which hand to use to complete the aiming movement on the subsequent trial (i.e., green=left hand, red=right hand). Consequently, blue LEDs were used in protocol 2 as targets instead of the red LEDs that were used in protocols 1 and 3. A banjo pick equipped with an infrared emitting diode (IRED) was attached to each index finger of the participant. These IREDs were tracked at a sampling rate of 500 Hz by the Optotrak system.[2]

The experimental approach employed to investigate facilitation and inhibitory processes was a target-target paradigm. The designs were a factorial arrangement of prior target, prior hand, target and aiming hand. In all protocols participants performed eight trial blocks of 29 aiming movements (i.e., 232 total trials) to the left or right target with either the left or right hand. The target order was always randomized between trials with the following constraints: (a) the same target-hand pairing was not repeated more than four times in a row, and (b) each target-hand pairing was presented an equal number of times throughout the experiment. Within a block of trials, the left and right target had an equal probability (i.e., 50%). Two catch trials were inserted randomly into each block of trials to prevent anticipations. As a result the trials following a catch trial were discarded from the analysis because there was no previous target or hand associated with those trials. Thus there were 24 experimental trials in each block. Same-hand and different-hand trials were presented differently between protocols.

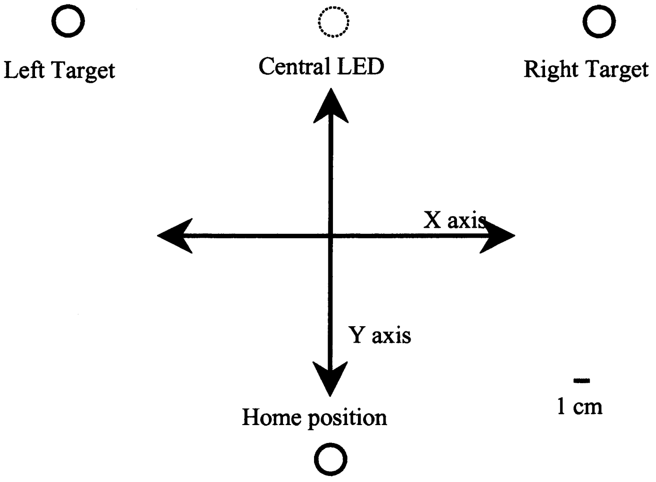

Fig. 1 Experimental setup

In the first protocol two blocks of trials were performed with the right hand, two blocks were performed with the left hand, and the remaining four blocks were performed alternating the hand from trial to trial. This blocking procedure provided us with an equal number of trials in each condition and also created a situation in which participants always knew in advance which hand was to be used on a given trial. It also allowed us to use a shorter intertrial interval than the second protocol in which the presentation of the same hand and different hand was randomized (i.e., with the constraint that each condition occurred equally often). The additional time for protocol 2 was associated with the presentation of a central cue indicating which hand to use on a particular trial. In the third protocol the central cue was withdrawn and participants were asked to alternate hand every second trial (e.g., right hand, right hand, left hand, left hand...).

Each series of trials involved a timed sequence of events that was triggered by the four-bank timer. In protocol 1 the events associated with a trial were as follows: an auditory warning signal and simultaneous initiation of Optotrak sampling, a 1.5-s foreperiod, onset of the target LED, and a 2.4-s delay that allowed the participant to complete his/her movement and return to the home position (intertrial interval 3.9 s). As well as the 1.5-s foreperiod in protocol 2 the sequence included an additional 1.4 s needed for onset and offset of the central cue that identified the hand to be used on that particular trial (intertrial interval 5.3 s). Protocol 3 was identical to protocol 1 except the delay to return to the home position was adjusted to 3 s (intertrial

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[2] Note that in protocols 1 and 3 the participants were not provided with any stimulus information at the central fixation point as the participants were in protocol 2. Despite this difference in presented stimulus information the participants in protocols 1 and 3 were told that it would be to their "advantage" to fixate centrally prior to the onset of the target as it would help to identify the location of the target more quickly (see also Tipper et al.1992; Welsh and Elliott 2004a). Given these instructions and the general acceptance of the instructions by the participants in previous work, it is assumed that there were no differences in the participants' use of the central fixation point between the different protocols.

interval 4.5 s). Thus the intertrial interval was intermediate relative to the first two protocols. In all three protocols participants were instructed to move to the appropriate target as quickly as possible when the target LED was illuminated and to land on the target with the tip of their finger so that the IRED was over the target. The uninvolved hand rested on the table top to the left or right side of the home position. From a theoretical point of view the three protocols were designed to answer the same questions related to inhibition, facilitation, and lateral asymmetries. The three separate procedures were employed to insure that any between-trial effects were not restricted to a specific intertrial interval or hand cuing/alternation procedure. An overview of the procedural differences between protocols appears in Fig. 2.

Data reduction

The raw displacement data were differentiated to obtain velocity. Following Chua and Elliott (1993), the beginning of a movement was defined as the first sample in which resultant velocity exceeded 30 mm/s and remained over that value for 72 ms (36 samples). The same velocity criterion was used to define the end of the movement; that is, it was the first sample at which the IRED velocity fell below 30 mm/s and remained there for 36 consecutive samples.

Results

Reaction time and movement time served as our primary dependent variables. These measures provide information about the time required to initiate and execute the movement, respectively. For all three protocols, separate 2 prior target (same, different)×2 prior hand (same, different)×2 target (left, right)×2 aiming hand (left, right) repeated-measures analyses of variance were conducted for each of these measures. Tukey's "honestly significantly different" test ($P \leq .05$) procedure was used to post hoc significant effects involving more than two means. For ease of presentation the inferential statistics (i.e., F) and probability values associated with each source of variation in this design are presented in Table 1. Here we also present a summary of the effect size for each F value greater than 1.0. Following Cohen (1988), we classified the effect sizes as follows: small, $F \leq .20$; medium, $F \leq .20–.40$; large $F \leq .40$. Because of the many similarities in our results across protocols, we have chosen to organize our results section according to each of the two dependent variables.

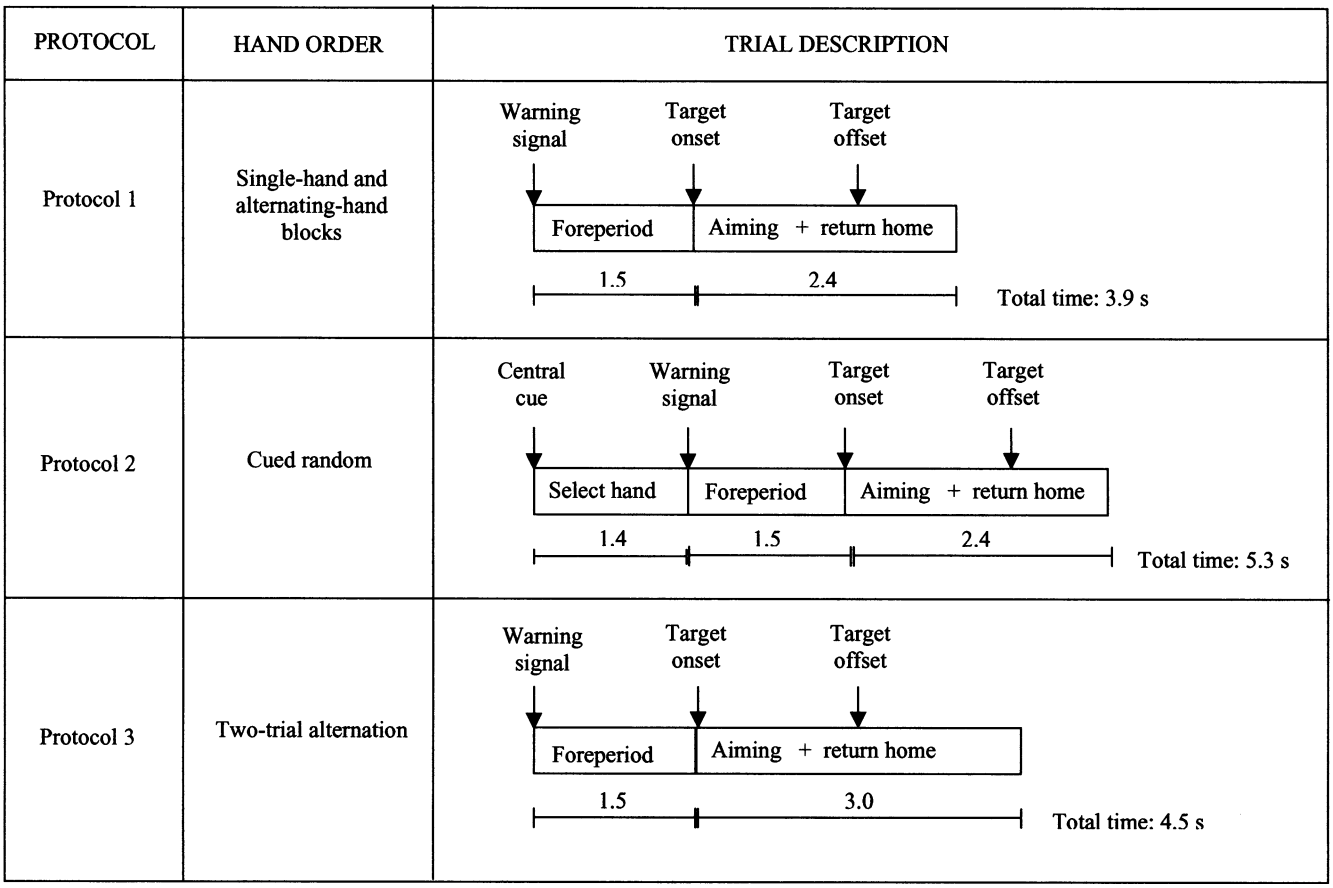

Fig. 2 Trial description and hand order for protocols 1–3

Table 1 *F* values and effect sizes (*Eff.*) associated with reaction time and movement time for the four-factor repeated-measures analyses in each of the three protocols (*S* small effect, *M* medium effect, *L* large effect)

	Reaction time						Movement time					
	Protocol 1		Protocol 2		Protocol 3		Protocol 1		Protocol 2		Protocol 3	
	F	Eff.	*F*	Eff.	*F*	Eff.	*F*	Eff.	*F*	Eff.	*F*	Eff.
P-hand	29.06**	L	8.30*	M	14.22**	M	1.21	S	3.15	S	2.4	S
P-target	10.36**	M	0.84	–	22.63**	S	14.16**	S	6.78*	S	35.08**	M
Hand	0.35	–	0.74	–	0.79	–	21.67**	L	25.82**	M	0.06	–
Target	5.81**	S	2.25	S	2.87	S	0.92	–	0.55	–	0.43	–
P-hand, P-target	7.46*	S	12.05**	S	7.39	S	4.70***	S	9.76***	S	8.36*	S
P-hand, hand	0.33	–	5.18*	S	1.82	S	1.80	S	25.34**	S	6.95*	S
P-target, hand	0.003	–	13.60**	S	1.22	S	19.12**	S	16.45**	S	2.13	S
P-hand, target	1.57	S	0.9		9.29	S	0.02	–	0.02	–	0.007	–
P-target, target	2.08	S	1.61	S	0.51	–	0.9	–	0.52	–	2.63	S
Hand, target	0.07	–	3.77	S	4.24***	S	58.67**	L	63.58**	L	3.54	M
P-hand, P-target, hand	2.49	S	0.9	–	21.10**	M	9.26*	S	11.35**	S	1.77	S
P-hand, P-target, target	0.35	–	1.07	S	0.01	–	0.93	–	11.49**	S	0.85	–
P-hand, hand, target	0.17	–	0.03	–	0.73	–	0.11	–	0.47	–	1.21	S
P-target, hand, target	17.27**	S	1.25	S	14.48**	S	0.02	–	2.84	S	0.31	–
P-hand, P-target, hand, target	0.44	–	1.75	S	0.08	–	0.003	–	3.49	S	4.24***	S

**$P<.01$, *$P=<.05$, ***$P=.06$

Reaction time

In all three protocols there was a main effect for previous hand, with participants responding more quickly when the movement for a particular trial involved the same hand as on the previous trial. In protocols 1 and 3, there was also an overall effect for prior target, which involved participants responding more slowing when the same target appeared on consecutive trials. These main effects were mediated by a prior hand by prior target interaction in all three protocols. As is evident in Fig. 3, the inhibition associated with returning to the same target was only significant when participants used a different hand on trial N and trial N+1. A three-way interaction involving hand in protocol 3 revealed participants were especially slow initiating a movement with their right hand when the previous response was towards a target associated with the left hand (318 ms) but fast when it was required to return to a target position that it had just left (279 ms, $P \le .05$; see Table 1). This facilitation, specific to the right hand, was evident in movement time instead of reaction time for protocols 1 and 2 (see below).

Other reaction time effects of interest all included the influence of target. In protocol 1, a prior target by hand by target interaction revealed that participants had particular difficulty when moving the right hand to a prior target in left space compared to right space ($P \le .05$, Fig. 3). This asymmetry could indicate that the right hand system is more susceptible to IOR effects associated with location but only when operating in contralateral space. In protocol 3 the same interaction indicated that both left hand and right hand reactions times were significantly longer when returning to a target in contralateral space (Fig. 3). Once again it appears that it is more difficult for a limb to overcome inhibitory processes when it must cross the midline.

Movement time

As we anticipated, main effects for hand in protocols 2 and 3 revealed that participants were faster at completing their movements when aiming with the right hand. Although participants were slower at initiating their movements to the same prior target, in all three protocols, participants executed their movements to the same prior target in a shorter period of time. In all three protocols this main effect for prior target was mediated by an interaction involving prior hand and in the case of protocols 1 and 2 a three-way interaction that included aiming hand. As is evident in Fig. 4, same target advantages were significant only when the movements were performed with the same hand. For protocols 1 and 2 the participant enjoyed an advantage when returning to the same target with the right hand but not with the left hand. This pattern of asymmetry for movement time in protocols 1 and 2 is similar to the pattern of right hand facilitation for reaction time in protocol 3.

The other effects of interest all involved target. In protocols 1 and 2 significant hand by target interactions revealed that each hand performed best in its own hemispace ($P \le .05$). An examination of various kinematic markers indicated that in all three protocols participants achieved higher peak velocities earlier in the movement when aiming in ipsilateral space (e.g., protocol 2 peak velocity: ipsilateral 966 mm/s, contralateral 793 mm/s, $F_{(1,10)}=37.57$, $P \le .001$; protocol 2 time to peak velocity:

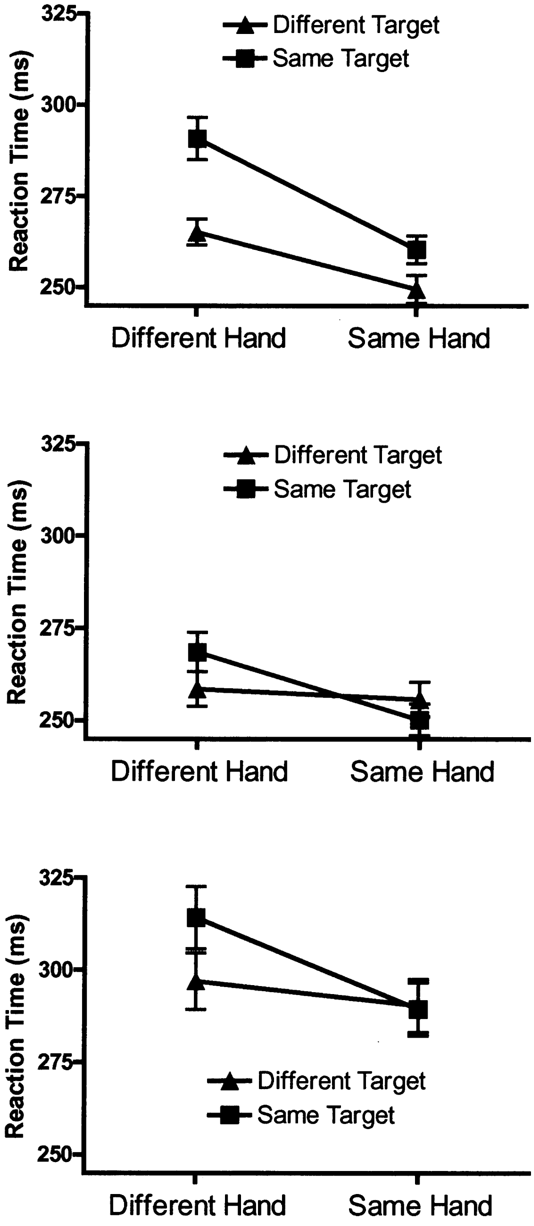

Fig. 3 Reaction time and standard error of the mean as a function of prior hand and prior target in protocol 1 (*top*), protocol 2 (*middle*), and protocol 3 (*bottom*)

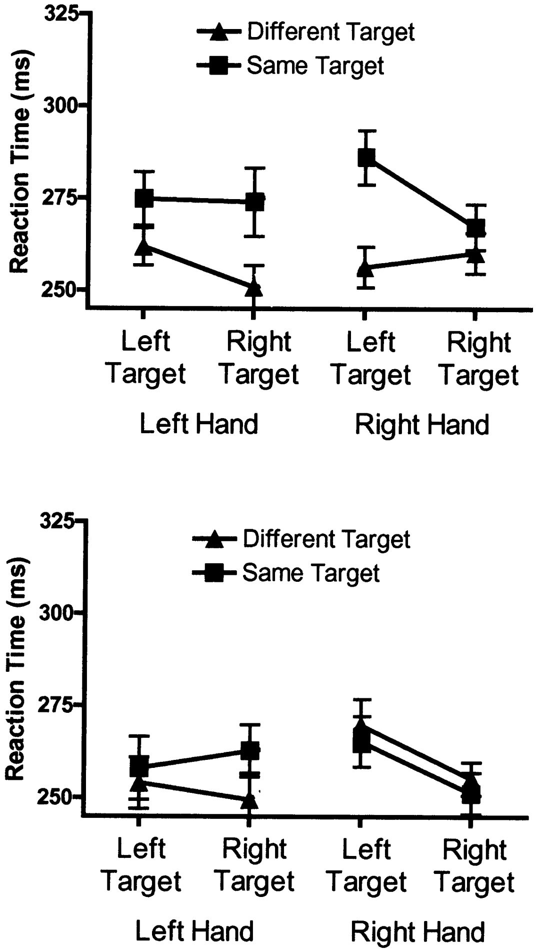

Fig. 4 Reaction time and standard error of the mean as a function of prior target, hand, and target in protocol 1 (*top*) and protocol 3 (*bottom*)

ipsilateral 126 ms, contralateral 167 ms, $F_{(1,10)}$=112.37, $P \leq .001$).[3]

In the case of protocol 2 a three-way interaction for movement time involving target indicated that when moving in left space, participants performed best when returning to the same target with the same hand, and worst when moving to the same target with the other hand ($P \leq .05$). For movements in right space, however, the most difficult situation involved a change for both the effector and the target (see Table 2). Given the robust nature of the hand by target movement time effects in protocols 1 and 2 (see Table 2), we were surprised that this effect did not reach conventional levels of significance in protocol 3 particularly when the effect size was medium to large (F=.34; see Cohen1988). Reexamination of individual participant data indicated a very large mean square error for this effect.

Because reaction time and movement time effects were sometimes in opposite directions, we examined the within-participant relationship between reaction time and movement time. For this analysis within-person across-trial correlation coefficients were generated for each experimental condition and converted to Fisher's Z scores. These scores served as data in the same type of factorial analysis conducted on reaction time and movement time.

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[3] For protocol 2 the peak velocity analysis also revealed a prior hand by hand interaction ($F_{(1,10)}$=13.93, $P \leq .01$. Specifically right-hand movements that followed right-hand movements achieved significantly higher peak velocities (885 mm/s) than left-hand movements that followed left-hand movements (864 mm/s), while there was no difference between the right hand (878 mm/s) and left hand (882 mm/s) peak velocities when the prior hand was different. This finding is consistent with the idea that movement time facilitation effects associated with the right hand are due to feedforward processes.

Table 2 Mean ±SD of each experimental condition for reaction time and movement time for the three protocols

	Reaction time			Movement time		
	Protocol 1	Protocol 2	Protocol 3	Protocol 1	Protocol 2	Protocol 3
Different hand						
Different target						
Left hand						
Left target	270±6	254±10	292±16	468±14	380±21	439±29
Right target	263±8	251±10	310±15	497±15	447±18	470±30
Right hand						
Left target	259±8	272±10	283±17	485±14	416±18	482±34
Right target	267±8	256±6	303±13	440±11	368±16	446±29
Same target						
Left hand						
Left target	290±11	269±14	297±16	459±14	394±19	434±24
Right target	288±16	266±10	324±20	498±18	428±19	450±30
Right hand						
Left target	300±11	278±11	318±17	474±15	424±19	473±33
Right target	285±8	262±8	318±16	436±16	356±16	440±33
Same hand						
Different target						
Left hand						
Left target	253±8	254±10	282±17	464±16	404±24	450±28
Right target	238±7	248±10	291±15	499±17	429±18	483±28
Right hand						
Left target	253±8	267±10	292±13	484±21	413±22	476±33
Right target	253±8	254±7	296±14	441±19	361±19	451±32
Same target						
Left hand						
Left target	260±8	248±10	290±14	459±13	386±19	431±27
Right target	260±8	260±11	310±17	497±18	454±18	465±35
Right hand						
Left target	272±8	253±7	290±14	447±15	381±18	447±27
Right target	250±5	241±7	269±12	405±15	323±14	382±27

Z score analysis

The analysis of *Z* scores failed to reveal any reaction time-movement time relationships that were different from zero ($P \leq .05$). In protocol 1 the *Z* scores in the 16 conditions ranged from −.034 to +.119 with a grand mean of +.021. In protocol 2 individual condition means ranged from −.061 to +.330 (grand mean +.079), and in protocol 3 from −.034 to +.307 (grand mean +.052). Thus at least within participants there were no reaction time-movement time tradeoffs.

Discussion

Discussion of protocols 1–3

This study examined trial-to-trial inhibition and facilitation in three different target-target aiming protocols. Our results were generally consistent across the three experimental procedures. In both protocols 1 and 3 there was an overall inhibitory effect for reaction time associated with a prior target. That is, participants were slower in initiating movements to a target that had served as the stimulus on the previous trial than to the other target. In these protocols this overall inhibitory effect was mediated by an interaction involving prior hand. This same interaction was also apparent in protocol 2. Participants were disadvantaged only when returning to the same target when using the hand that had not been involved on the previous trial. Thus IOR for reaction time in this target-target paradigm appears to be more associated with target location than with either the effector or the specific movement that is organized to accomplish the movement goal. In fact, in all three protocols performing with the same hand two times in a row resulted in a distinct reaction time advantage relative to the situation in which participants were required to change hands. It would appear then that both prior target inhibition and prior hand facilitation operate in parallel to determine movement initiation times. Consistent with attentional explanations of IOR (e.g., Abrams and Dobkin 1994), either an area in space or the area around a specific perceptual object may be inhibited following a presentation in order to allow the organism to shift attention to new and different perceptual events. These inhibitory effects are not diminished and in fact increase when a different effector is used to perform the movement. This finding is not consistent with an action-based explanation of IOR and, although not precluding the idea that inhibitory processes are working at another level of the responding system (Welsh and Elliott 2004b), suggests that target localization and movement preparation are not the same process.

The facilitation effect for reaction time, associated with prior hand, probably reflects movement organization activities that take place during the reaction time interval after the target has been identified. Specifically, when the same effector is used two times in a row, there may be no need to reparameterize "hand" in the motor program that has been developed to complete the aiming movement on the preceding trial (e.g., Rosenbaum1980). This of course would result in a temporal savings.

Facilitation effects associated with repeating a movement could account for some of the differences in the IOR literature between cue-target and target-target findings. Specifically, target-target IOR effects may be smaller (Tassinari et al.2002) and less consistent (e.g., Spence and Driver1998) than cue-target effects because there is a parallel facilitation effect associated with always using the same hand. In the other hand-same target conditions in this research, the advantage associated with repeating exactly the same movement was removed.

Although both same-target inhibition and same-effector facilitation appear to have their independent effects on reaction time, of equal interest was how these effects are mediated by specific target-hand combinations. For example, there is some evidence that the right hand may be more susceptible to inhibitory effects than the left hand. Specifically, participants were especially slow at initiating right hand movements when these movements involved returning to a prior target in left space (protocols 1 and 2). Interestingly, the different-target reaction time advantage for both hands was most pronounced in left space (protocol 3). These finding may be due the special role the right cerebral hemisphere has in the distribution of attentional resources (for a review see Marzi1999). Perhaps the right cerebral hemisphere is able to establish a more potent inhibitory field in left space than can be established in right space.[4] This left-sided inhibitory field has its greatest effect on the right hand system. While the right hemisphere-left side system appears to be more instrumental in determining inhibitory effects than the left hemisphere-right side system, facilitation effects appear to be more associated with the left hemisphere-right hand system. In terms of reaction time the right hand enjoys a greater advantage repeating exactly the same movement than the left hand (protocol 3). This hand asymmetry is also apparent for movement time.

In both protocols 1 and 2 our analysis of movement time revealed a three-way interaction involving prior hand, prior target, and hand. Overall the right hand acquired target positions more rapidly than the left hand, this was especially the case when the right hand was returning to a target that it had just vacated. Once again, this specific right hand advantage may reflect the ability of the left cerebral hemisphere to maintain a parameterized movement pattern over an intertrial interval of 5 s or more. This facilitates movement execution in the second of the two identical aiming attempts. For the left hand this same facilitation of movement time was not apparent. Although this three-way interaction for movement time was absent in protocol 3, there was a prior target by hand interaction. In this protocol a consecutive trial right hand advantage was evident regardless of whether the right hand was returning to the same target or moving to a different target. Presumably, even partial parameter overlap entails some temporal savings for the right hand (i.e., no need to reparameterize hand). In spite of the absence of any reaction time-movement time trade-off, it is interesting that for protocol 3 the more specific facilitation associated with both target and hand was apparent in reaction time rather than movement time (cf. protocols 1 and 2). In this context, it is interesting that the overall mean reaction time was slightly longer in protocol 3 than in the other two situations.

Other more standard movement time asymmetries were also apparent in our data. Specifically, both the right arm and the left arm performed best in ipsilateral space. This could either reflect a within-hemisphere processing advantage (Elliott et al.1993) or a biomechanical advantage (Carey and Otto-de Haart2001). While overall the right hand enjoyed a movement time advantage, contrary to other work from our laboratory (e.g., Mieschke et al.2001), the left hand did not exhibit a reaction time advantage (for a review see Carson1992). This could reflect the fact that spatial uncertainty in this experiment was limited to two targets.

Because inhibitory asymmetries were more pronounced for reaction time, and facilitation asymmetries were more pronounced for movement time, we examined the reaction time-movement time relationship to make sure that there were no differential tradeoffs across experimental conditions. When different from zero, any reaction time-movement time relationships were slightly positive, indicating that individual participants were not trading-off the two variables. Overall our results appear to reflect the independent contribution of perceptual/movement planning processes and movement execution processes.

General discussion

The past decade has seen the advent of a number of action-based models of visual selective attention (Rizzolatti et al.1994; Tipper et al.1992; Welsh and Elliott 2004a). Common to all of these models is the idea that turning one's attention to a position or object in space may involve

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[4] Cherry and Hellige (1999) have reported left space-right hemisphere advantages for sustained attention that are mediated by the hand used to detect a visual signal. In the case of our IOR protocol it may be that this type of attentional asymmetry is associated with the right hemisphere being able to maintain inhibition, as opposed to vigilance, over a longer period of time.

some of the same processes as preparing an eye or limb movement to that location/object. Action-based models of selective attention have done a good job of explaining interference effects associated with competing targets (Meegan and Tipper1998,1999) as well as negative priming (Tipper et al.2002) and IOR in a cue-target task (Briand et al.2000; Welsh and Elliott 2004b).

Given that distractor interference, negative priming, and inhibition of return may all involve the same attentional/movement planning process (e.g., Milliken et al.2000), we thought it would be instructive to determine whether IOR in target-target aiming generalizes across effector. This question was developed in the context of a movement organization literature that suggests there are invariant characteristics of any "motor program" that are effector independent (Raibert1977). However, for any specific movement to unfold a generalized motor program must be parameterized so that specific task demands can be met (Schmidt1976). Parameterization could involve the specification of the effector (e.g., the left hand or the right hand), the specific muscle group (e.g., flexors or extensors), or perhaps the absolute force associated with a series of muscle contracts. This parameterization process takes time (e.g., Rosenbaum1980), and thus there may be a temporal savings associated with performing exactly the same movement two times in a row (see Rosenbaum et al.1987). These movement preparation phenomena could lead to movement facilitation under exactly the same conditions in which we might expect IOR (i.e., using the same effector and same muscle group to return to exactly the same position in space).

Consistent with the visual attention and the motor programming literature, we found both IOR and facilitation associated with repetition of the same movement. Interestingly, inhibition effects were more apparent for reaction time and facilitation effects were apparent for both reaction time and movement time. As well, inhibition was more evident when a right-hand movement followed either a left-hand movement to the same target or a movement in left space. This asymmetry could reflect the special role the right cerebral hemisphere plays in the allocation of attentional resources (e.g., Marzi1999), in combination with a left-hemisphere (i.e., right-hand) inability to override any inhibitory field established by this system around a specific target location and/or movement field. Although the right-hemisphere (left-side) system appears to have precedence for attentional/inhibitory effects (Heilman1979), it is the left-hemisphere (right-side) system that appears to enjoy a motor programming and therefore facilitation advantage. This asymmetry probably reflects the special role the left cerebral hemisphere plays in the organization and control of movement (for a review see Elliott and Chua1996). Specifically, the right hand system was able to maintain a parameterized plan for a specific target aiming movement over the trial N to trial N+1 interval. This resulted in a small reaction time advantage and a larger advantage in the time necessary to execute the movement.

In sum, it appears that separate perceptual and one or more motor process contribute to trial-to-trial effects in target directed aiming. Moreover, temporal effects associated with both IOR and facilitation appear to be mediated by the specific visual space-limb pairings involved in the aiming movements. In this context, it would be interesting to determine whether inhibition and/or facilitation occurs in an across effector pairing that involves saccadic eye movements and left or right arm movements. With respect to spatial and manual asymmetries it would also be interesting to conduct a study using a four-target array where a target can be in the same hemispace but not in the identical location.[5]

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