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The processes of facilitation and inhibition in a cue–target paradigm: Insight from movement trajectory deviations

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ABSTRACT

Several researchers have examined the trajectories of aiming movements in cue-target paradigms to investigate the motoric and attentional underpinnings of the inhibition of return (IOR) effect. The results of separate studies have revealed inconsistent patterns of trajectory deviations. These discrepancies may have arisen because the studies used narrow ranges of cue–target onset asynchronies (CTOAs) which may have prevented the time courses of facilitation and inhibition effects to be fully assessed. The present study was designed to conduct an examination of temporal and spatial characteristics of aiming movements over a broader range of CTOAs to provide a more comprehensive assessment of the potential expression of attentional and motoric contributions to cuing effects. Participants aimed to targets which were preceded by a non-predictive cue at CTOAs of 100, 350, 850, and 1100 ms. Analysis of spatial and temporal characteristics of the movements revealed facilitatory and inhibitory cuing effects in the trajectories, but only inhibitory cuing effects in RT. Further, the inhibitory effects in RT appeared at a shorter CTOA than the inhibitory effects in trajectories. This pattern of results suggests that the inhibitory mechanisms underlying IOR affect both attention and motor systems, but that these effects are displaced in time.

1. Introduction

One common method for investigating the processes of the involuntary capture of attention is a cue–target paradigm in which a non-predictive cue is presented at one of a number of potential target locations. The interval of time between the onset of the cue and the target (the cue–target onset asynchrony or CTOA) is varied in these tasks in an attempt to understand how the capture of attention by the cue subsequently influences the processing of the target information and the response to the target. Response times are typically shorter for cued targets than for uncued targets at short (<100 ms) CTOAs, but are longer for cued targets than for uncued targets at longer (>200–300 ms) CTOAs (e.g., Posner & Cohen, 1984). This pattern of response times is thought to reflect a set of mechanisms which facilitate and then hinder or inhibit the orienting of attention to, the further processing and selection of a response to a target at the location of the cue (Klein, 2000; Posner & Cohen, 1984; Prime & Ward, 2004; Samuel & Kat, 2003; Wilson & Pratt, 2007). The latter inhibitory mechanisms that lead to longer response times on cued target trials, commonly known as the inhibition of return (IOR) effect, have been the subject of intense investigation and debate.

Theoretical explanations of IOR have included perceptual/attentional-based mechanisms that affect the detection and processing of the target, and action-based mechanisms that affect the response to the target (Abrams & Dobkin, 1994; Coward et al., 2004; Reuter-Lorenz et al., 1996; Taylor & Klein, 2000; Welsh & Pratt, 2006; see Klein, 2000 for a review). Most studies of IOR have used a key press response and, as a result, only total response time and response errors were examined. In an attempt to gain a deeper understanding of the attentional and motor explanations of IOR, a number of investigators have asked participants to complete rapid, goal-directed reaching movements toward the target and analyzed movement trajectories and endpoints in addition to reaction time. Goal-directed movements were used because the analysis of a number of kinematic variables such as trajectories can provide additional insight into the influences of cognitive processing on motor system activation and action planning (for review, see Song & Nakayama, 2009).

In short, movement trajectories can provide additional insight into the dynamics of cognitive processing because movement direction is represented, in part, by populations of directionally-tuned neurons in the motor system (e.g., Georgopoulos, 1995). It has been suggested that the initial direction of a movement is the vector sum of the activation levels of each competing response code generated from stimuli in the environment. Thus, it is held that the movement trajectories reflect the activation state of simultaneously represented stimuli. In the present context of cue–target paradigms and IOR, it was predicted that movements on uncued target trials should deviate toward the

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cue at short CTOAs as the response to the cue will still be partially activated, and away from the cue at longer CTOAs because the response to the cue should be inhibited to below a baseline level. With the response to the cue below baseline level, the resultant response vector should code for a movement direction away from the location of the cue (Howard & Tipper, 1997; Welsh & Elliott, 2004b).

Howard et al. (1999) conducted the first testing of trajectory deviation predictions and contrasted them with attentional, RT effects in a cue–target paradigm. They required participants to point to targets to the left or right of midline and analyzed effects of the timing and location of the preceding cue on movement trajectories. Consistent with the literature on IOR, RTs to cued targets were longer than to uncued targets at both CTOAs that were used (200 and 600 ms). The analysis of trajectories, however, revealed that the movements veered toward the cue with the shorter 200 ms CTOA and that there was no effect of the cue on trajectories with the longer 600 ms CTOA. Based on this pattern of findings, the authors suggested that the cue may activate portions of the motor system (causing the deviations toward the cue at the short CTOA), but the activation rapidly decays without any inhibitory after-effects.

In a subsequent study, Chang and Ro (2005) did find evidence of late inhibitory effects on motor output. Participants in their study reached from a central start position and pointed to a target that appeared on either side of the start position along the horizontal meridian. Notably, these aiming movements in the first experiment were completed without vision of the hand. The targets were preceded by a cue that appeared at one of the potential target locations either 200 or 750 ms before the target. RT, movement amplitude, and movement endpoint were analyzed. The authors predicted that if there was a motoric component to the IOR effect, then reduced movement amplitudes and endpoint biases toward the center would be observed due to inhibition of the response to the cue. Consistent with previous research, there were longer RTs to cued targets at both CTOAs indicating the activation of an inhibitory mechanism. There were, however, only reduced movement amplitudes and end points closer to the start position on cued target trials in the 750 ms condition. Because the spatial results were similar to a previous study by the authors that used saccades rather than pointing movements in a similar paradigm (Ro et al., 2000), they concluded that motor account of IOR was plausible as comparable effects were found across different effector systems.

Although the Chang and Ro (2005) study provides some support for inhibitory mechanisms working at the level of the motor system, the use of movement amplitude and endpoint as measures may not provide a comprehensive picture because movement endpoints are influenced by both the planning and corrective mechanisms underlying motor control (see Welsh, 2011; Welsh & Weeks, 2010). That is, reaching movements consist of an initial ballistic phase where the hand is brought closer to the target that is followed by a correction phase where fine adjustments are made to bring the finger accurately to the target (Woodworth, 1899; see Elliott et al., 2001 for review). Characteristics of the early ballistic phase are thought to predominantly reflect the results of movement planning, whereas end characteristics such as movement endpoint are affected by online corrections based on either visual or proprioceptive feedback from the movement. Thus, one might develop an incomplete picture of the inhibitory influences on the motor system if one relies solely on measures of movement termination, such as endpoint and amplitude because the correction processes may ameliorate the error-causing effects that such inhibitory mechanisms of IOR may have on the earlier planning stages. Consistent with this proposal, in a second experiment by Chang and Ro (2005), participants moved a cursor to targets on a screen which was on a different plane from the movement plane of the hand to dissociate the movement from the stimulus. A cursor on the screen gave feedback of their movement which allowed for online corrections to the movements. In this study, no effect of the cue on movement amplitude or endpoint was observed. Chang and Ro argued that the absence of endpoint error in this "dissociated" cursor aiming task was evidence that direct motor interaction with the target is required for motoric effects of IOR to emerge. It is possible, however, that there were no influences of the cue on movement endpoint in the second experiment because the addition of visual feedback allowed for more effective online corrections, masking any cueing effects.

Finally, Welsh and Elliott (2004a) also observed inhibitory effects in both the temporal and spatial measures of movement. They employed a methodology similar to Howard et al. (1999) in that participants aimed to one of two target locations. The critical difference in the methods, however, was that they used a longer range of CTOAs (from 700 to 1400 ms). At these CTOAs, Welsh and Elliott (2004a) observed both longer RTs on uncued- than cued target trials as well as movement trajectories that deviated away from the cued location on uncued-target trials. This pattern of effects is consistent with motoric contributions to IOR.

In sum, previous studies have revealed different patterns of facilitation (Howard et al., 1999) and inhibition (Chang & Ro, 2005; Welsh & Elliott, 2004a) in goal-directed movement patterns following non-predictive cues. Note, however, that the reaching studies involved different ranges of CTOAs and dependent measures. As a result, the absence of a consistent picture across these studies may be due to the varying measures and the limited ranges of CTOAs used in each individual study. Thus, a more comprehensive examination of the time course of inhibition and facilitation in the motor system is required to provide a more complete picture of the nature of the attentional and motoric mechanisms underlying cuing effects and IOR in manual aiming movements.

1.1. Purpose and hypotheses

The present study was designed to clarify the nature of the attentional and motoric contributions to cuing effects by conducting a single study with a more comprehensive range of CTOAs. To this end, participants completed aiming movements to targets presented 100, 350, 850, or 1100 ms after a non-predictive cue. These CTOAs were chosen because they extend the range used in previous studies, as well as allow for a more consistent comparison to the pattern of facilitatory and inhibitory effects that have been extensively explored in keypress tasks (e.g., Posner & Cohen, 1984; Samuel & Kat, 2003). RTs and movement trajectory deviations on the axis perpendicular to the direction of movement were analyzed. If the motor system is the main driver behind the facilitatory and inhibitory effects associated with the presentation of the cue, then the time course of the pattern of trajectory deviations toward and away from the cue should be similar to the time course of facilitation and inhibition in RTs. On the other hand, if cuing effects are due to attentional and perceptual mechanisms with either secondary or separate effects on the motor system, then the time course between the two measures should differ.

2. Method

2.1. Participants

Five female and seven male (n = 12) right-handed students from the University of Toronto participated in the study. The participants ranged in age from 18 to 33 years and had normal or corrected-to-normal vision. The procedures conformed to the Helsinki Declaration and were approved by the University of Toronto Ethics Board. Informed consent was obtained prior to data collection and participants received remuneration of $12 CAD for their time.

2.2. Apparatus and stimuli

Participants stood at a table in front of a 38 × 30 cm computer screen with 1200 × 960 pixel resolution that was titled so that the