

# Role of focal attention on latencies and trajectories of visually guided manual pointing

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Previous studies have shown that an odd-colored target among uniformly colored distractors can be rapidly detected and localized using broadly distributed attention over an entire display. In the current study, we show that such a broadly distributed attentional allocation is not sufficient for seemingly effortless goal-directed manual pointing. Latencies and movement durations of manual pointing in odd-colored search tasks become shorter and curved trajectories decreased as the number of distractors increase or target color repetitions increases. Because these manipulations have been shown to facilitate the deployment of narrowly focused attention to a target but not for distributed attention, this adds further support to the view that focal attention is necessary for goal-directed action. In addition, the presence of highly curved movement trajectories, directed first to a distractor then to the target reflects ongoing changes in focal attentional deployment and target selection.

Keywords: focal attention, distributed attention, perceptual grouping, perceptual priming, manual pointing

## Introduction

The visual system faces the daunting task of rapidly processing an enormous range of information in everyday perception. Within any given scene, the visual system must identify items, determine their layout, and finally guide actions to them (Allport, 1987, 1993; Neumann, 1987; Palmer, 1999; Thorpe, Fize, & Marlot, 1996). In order for humans to explore and interact successfully with an environment, one object out of several must be selected as the target for actions. Visual attention is crucial for selecting relevant information for visual perception (Nakayama, 1990; Pashler, 1998; Sperling, 1960) and actions (Allport, 1987, 1993; Neumann, 1987). For decades, the role of visual attention for perception has been extensively studied, addressing how fast and accurately participants can integrate and discriminate visual features, detect changes, or recognize targets (for a review, see Pashler 1998). Several studies have shown that a target among multiple distractors can be rapidly identified when the differences between the target and distractors are conspicuous such as color, orientation, size, and spatial frequency differences (Bergen & Julesz, 1983; Sagi & Julesz, 1985a, 1985b; Julesz, 1986; Koch & Ullman, 1985; Sagi & Wolfe, 1992; Treisman & Gelade, 1980). Thus, it shows that when there are salient perceptual differences between the target and distractors, broadly distributed attention for entire displays is sufficient to detect the target (Nakayama, 1990; Nakayama & Joseph, 1998).

Previous studies have also demonstrated that a pop-out target can be localized when it is detected without allocating focal attention to the target. *Focal* attention only needs to be directed to and zoom in on the target to identify target

features (Atkinson & Braddick, 1989; Folk & Egeth, 1989; Green, 1992; Johnston & Pashler, 1990; Sagi & Julesz, 1985a, 1985b).

For example, Sagi and Julesz (1985a, 1985b) demonstrated that when the mixture of horizontal and vertical line segments was presented among diagonal line segments, participants could rapidly count numbers of horizontal and vertical lines and could determine their positions as efficiently as detection, independent of the number of targets. The efficiency of localization process was examined by asking participants to discriminate the global shape of three oriented line segments, which formed the vertices of a triangle. To accurately distinguish different shaped triangles, positional accuracy of one or two line spacing between line segments was required. Therefore, this indicates that the target can be rapidly *detected* and *localized* simultaneously with broadly *distributed* attention, but target fine feature discrimination requires more time to allocate *focal* attention.

Bravo and Nakayama (1992) further examined visual search patterns in pop-out displays when attention was distributed throughout the whole stimulus array versus the case when it is focused on one specific stimulus (Nakayama, 1990). Figure 1 depicts the schematic diagram of the display (Figure 1A) and results (Figure 1B) from Bravo and Nakayama (1992). They showed that when participants were required to *detect* the presence or absence of an odd-colored diamond target among distractors (Figure 1B (c) and (d)), search times were relatively fast and did not vary with distractor numbers. This search pattern did not change regardless of whether target and distractor colors were kept constant from trial to trial as in Figure 1B (c) (*blocked* condition) or target and distractor colors were randomly

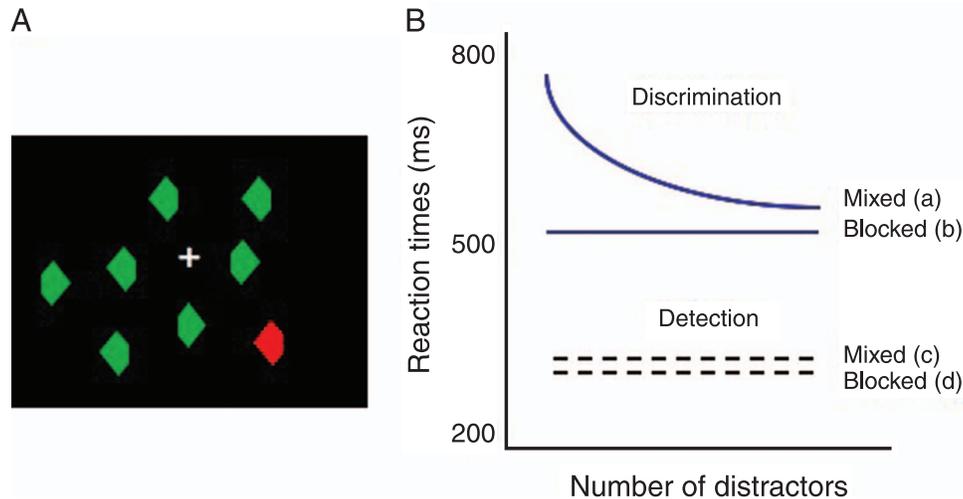


Figure 1. Schematic diagram of Bravo and Nakayama's (1992) visual search display (A) and reaction times (B).

switched between red and green from trial to trial as in Figure 1B (d) (*mixed* condition). This shows that when there are salient perceptual differences between the target and distractors, the broad scope of distributed attention is sufficient to detect the target. Thus, visual search patterns do not change based on the number of distractors or the consistency of target colors.

Yet, when participants were asked to discriminate detailed features such as a tiny cut-off corner side (Figure 1B (a) and (b)), reaction times became longer compared to simple detection performance because attention had to be directed to and narrowly *focused* on the target (Kristjansson, Mackeben, & Nakayama, 2001; Nakayama & Mackeben, 1989).

Moreover, two distinctive visual search patterns were observed depending on whether the target and distractor colors remained the same across trials. In the blocked condition (Figure 1B (b)), reaction times were constant regardless of the number of distractors. However, in the mixed condition (Figure 1B (a)), reaction times *decreased* as the number of distractors increased.

Bravo and Nakayama (1992) claimed that mechanisms directing focal attention to the target differ in the blocked and mixed conditions. In the blocked condition, when target and distractor colors remain the same, previous and current trials share the same attended target feature. This allows the short-term memory of the previous target to facilitate the rapid deployment of focal attention directly to the current target through *perceptual priming* (Maljkovic & Nakayama, 1994). Thus, the number of distractors does not influence visual search performance and result in a flat search slope (Figure 1B (b)). Yet, when target and distractor colors are switched unpredictably, as in the mixed condition, the rapid priming mechanism based on the same attended target features cannot be easily built up over time. Instead, a slower process of *perceptual grouping* must segregate the target from distractors before the narrowing of focal attention to the target. If perceptual grouping is strong, the target can pop-out more quickly and therefore focal

attention can be allocated more efficiently to the target (Nakayama & Joseph, 1998).

Overall, visual search performance is slower in the mixed condition than in the blocked condition. Moreover, because the perceptual grouping process is more efficient with larger numbers of distractors (Julesz, 1986; Koch & Ullman, 1985), reaction times are also reduced with increased distractor numbers (Figure 1B (a)).

Taken together, Bravo and Nakayama (1992) demonstrated conspicuously different behavioral patterns in the *detection* tasks using broadly distributed attention and *discrimination* tasks using narrowly focused attention (Figure 1B). When target feature discrimination is required, different visual search patterns are observed in the blocked and mixed conditions.

When McPeck, Maljkovic, and Nakayama (1999) applied Bravo and Nakayama (1992)'s visual search paradigm to saccades, they observed two distinctive saccadic search patterns in the blocked and mixed conditions, which were identical to the discrimination task (Figure 1B (a) and (b)). It is worth noting that discrimination of a subtle detail was not required in this saccadic task. Instead, McPeck et al. (1999) simply asked participants to make a saccade to an odd-colored target. This indicates that localizing the target for goal-directed saccades require more than simple detection of the target, which is quite different from findings of previous perceptual studies that target detection is sufficient to know where the target is (Atkinson & Braddick, 1989; Folk & Egeth, 1989; Green, 1992; Johnston & Pashler, 1990; Sagi & Julesz, 1985a, 1985b).

## Current study

In the current study, we aimed to investigate whether focused attention is also necessary for visually guided manual pointing by applying Bravo and Nakayama's (1992) paradigm.

In each trial, participants were asked to touch an odd-colored target among distractors with their index finger as quickly as possible. We emphasize that this manual-pointing task does not require any subtle target feature discrimination. Yet, if goal-directed pointing requires more precise localization of the specific target beyond target detection, this localization process will demand focal attention on the target. If this is the case, results from manual pointing are expected to show the same patterns observed in perceptual discrimination and saccadic tasks (Figure 1B (a) and (b)). Thus, the current study will verify whether focused attention required for saccades can be generalized to manual-pointing movements.

The close relationship between visual attention and saccades is particularly well documented. Regions of the brain responding to both eye movements and covert attention allocation have been identified by neuroimaging and neurophysiological studies, such as the frontal eye field, supplementary eye field, and several parietal and temporal regions (for reviews, see Corbetta et al., 1998; Schall & Thompson, 1999). Behavioral studies also have shown that saccades are preceded by the deployment of visual attention to the intended saccadic goal (Deubel & Schneider, 1996; Kowler, Anderson, Doshier, & Blaser, 1995; McPeck & Keller, 2001; McPeck et al., 1999; Schneider & Deubel, 2002).

The role of focused attention in visually guided manual actions, however, has been relatively less well studied than saccades. A few pioneer studies have demonstrated the connection between attention and reaching (for a review, see Castiello, 1999). For example, Deubel, Schneider, and Paprotta (1998) demonstrated that the ability to discriminate a briefly presented stimulus was improved when participants pointed to a location where a stimulus for discrimination appeared. Tipper and his colleagues showed that when participants reached for a prespecified target, their reaching trajectories swerved away from a distractor in the moving path (Tipper, Howard, & Houghton, 1998; Tipper, Lortie, & Baylis, 1992). Yet, it is not entirely clear whether distributed attention is sufficient or if focused attention is necessary for visually guided manual pointing in particular when multiple competing distractors are presented.

Eye and hand movements frequently demonstrate similar spatiotemporal characteristics (Ballard, Hayhoe, Pook, & Rao, 1997; Land & Hayhoe, 2001; Land & McLeod, 2000; Neggers & Bekkering, 2000, 2002). However, eye and hand movements are not only controlled by different neural mechanisms but also serve different purposes. Eye movements are typically made to foveate the target, but most hand movements are made to reach for selected objects in the external world (Cisek & Kalaska, 2005; Pratt, Shen, & Adam, 2004). Furthermore, traditional cognitive theories of human behaviors have assumed that perception, cognition, and action comprise serially distinct stages (Marr, 1980; Newell & Simon, 1972; Sanders, 1980; Sternberg, 1969). In this scheme, eye movements are closely connected to perceiving visual objects and providing relevant information

for decision-making process whereas arm movements are often regarded as mere reflections of completed cognitive decisions (Cisek & Kalaska, 2005). Focused attention required for subtle target features could be only required for saccades but not reaching.

Thus, there is no obvious reason to assume that the same attentional mechanism must or must not be involved in target localization for manual pointing as in saccades. Whether focused attention is commonly involved in saccades and reaching is rather an empirical issue, which should be thoroughly examined.

We decided to measure the full trajectory over the entire time course of pointing because it could reveal changes in target selection and motor plans over time (Arai, McPeck, & Keller, 2004; Jeannerod, 1988). Movement trajectories and duration might also tell us whether motor actions simply carry out a completed decision for the correct target as viewed in traditional theories (Marr, 1980; Newell & Simon, 1972; Sanders, 1980; Sternberg, 1969) or more interactively involved in decision-making processes (Cisek & Kalaska, 2002, 2005; Tipper et al., 1992, 1998). If reaching only reads out completed visual decision, target selection processes would affect only the initiation latency of manual pointing but not movement trajectory and duration.

## General methods

### Participants

Harvard University students participated for course credit. They were all right-handed with normal color vision and normal visual acuity. Each of the seven participants participated in Experiments 1 and 2.

### Stimuli

The solid, red, or green diamond-shaped stimuli ( $1.5^\circ \times 1.5^\circ$ ) were presented against a black background. The red and green were chosen to be approximately equiluminant using flicker photometry. The stimuli were arranged uniformly around an imaginary circle with a radius of  $14^\circ$ . The target was positioned randomly from trial to trial at one of three possible positions, corresponding to 4, 8, and 12 o'clock in relation to the fixation.

### Task

Participants were tested individually in a semidarkened room. They were seated 48 cm in front of the visual display. In the manual-pointing task, participants were required to touch an odd-colored target among distractors with their index finger (Figure 1A). If the target was red then the

distractors were green, and vice versa. In each trial, the black screen with a white fixation cross was presented for 700–900 ms. Participants were required to fixate on the cross throughout the trial. The fixation cross was always in the middle of the stimulus configuration.

The target and distractors were present on the screen until the participants responded. When participants touched the item (within stimulus + 0.75° surrounding area), a beep indicated whether participants selected the correct target. The intertrial interval was 700 ms.

## Measuring hand movements

Hand movements were tracked with a Fastrak electromagnetic position and orientation measuring system (Polhemus Inc.) with an update rate of 120 Hz. The small position-tracking sensor (0.89" × 0.50" × 0.45") was attached to the index fingertip of the right hand. The starting position (3 cm × 3 cm) was marked on the table, which was approximately aligned with the body midline and 20 cm in front of the participants. Participants were required to put their index finger on the starting position to initiate each trial. The tracking system was calibrated in each block with 9 distributed points.

## Data analysis

Movement data were transmitted to a Power Mac G4 by Vision Shell library for off-line analysis to identify the onset of movements. Hand velocity exceeding a threshold of 10 cm/s demarcated the onset of the movement. Each trajectory was visually inspected to verify the appropriateness of this criterion.

Only trials in which participants touched the correct target were included for further analysis. *Initiation latency* was defined as the interval between stimulus and movement onsets. *Movement duration* was the interval between movement onset and offset. *Total time* was the sum of *initiation latency* and *movement duration*. Trials in which latencies were below 100 ms or total times were in excess of 1500 ms were excluded as anticipatory movements and outliers. Less than 3% of the trials were eliminated because of selection errors or latency criteria.

We characterized the global movement trajectory by computing *maximum curvature* (Desmurget, Jordan, Prablanc, & Jeannerod, 1997). *Maximum curvature* is defined as the ratio of the largest deviation (perpendicular distance) of the trajectory from the straight line connecting the start and end points (target position) of the movements to the length of this line (Arai et al., 2004; Atkeson & Hollerbach, 1985; Desmurget et al., 1997; McPeck & Keller, 2001; Smit & Van Gisbergen, 1990). Thus, maximum curvature was computed in each trial with respect to the target position. For example, maximum curvature of zero means a straight trajectory.

## Experiment 1

In **Experiment 1**, we investigated whether focal attention needs to be directed to the target for manual pointing and how the entire course of manual-pointing movements is affected by attention allocation. Two aspects of the trial were manipulated in odd-colored search tasks: the number of distractors and the consistency of target colors across trials (blocked and mixed conditions) (Figure 2). The number of distractors randomly varied between 2, 5, and 11 in each trial. In the mixed condition (Figure 2A), target and distractor colors were randomly switched from red to green in each trial, whereas in the blocked condition (Figure 2B), target colors remained the same within a block.

If target detection using distributed attention suffices to localize targets for manual pointing, the search slope should be flat regardless of the number of distractors and the consistency of target colors as in Bravo and Nakayama's (1992) detection task (Figure 1B (c) and (d)). However, if target localization requires the allocation of focused attention to the target, two distinctive search patterns should be observed in the mixed and blocked conditions (Figure 1B (a) and (b)).

## Methods

Participants performed manual pointing for 2 blocks of each mixed and blocked condition (72 trials/block). The

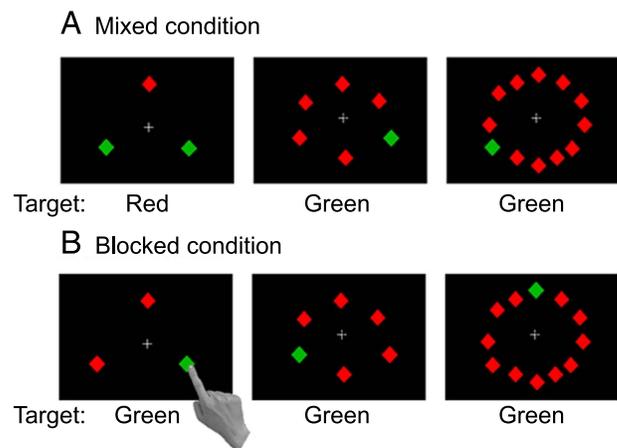


Figure 2. Schematic diagram of experimental conditions in **Experiment 1**. Participants were asked to search for and touch an odd-colored target among distractors with their index finger. Two aspects of trials were manipulated: the number of distractors and the consistency of target colors across trials. The number of distractors randomly varied between 2, 5, and 11 in each trial. In the mixed condition (A), the target and distractor colors were randomly switched from red to green in each trial, whereas in the blocked condition (B) target colors remained the same within a block.

order of the mixed and blocked conditions was randomly assigned across participants. In addition, randomly switched red or green single targets (48 trials/block) were presented without distractors at the beginning and end of the manual-pointing task as a baseline. There were 50 practice trials. Each participant experienced all the conditions and repeated ANOVAs were conducted for statistical analysis.

## Results and discussion

### Manual-pointing reaction times

#### (1) Total time

Patterns of *total time* exactly mirrored those of Bravo and Nakayama's (1992) discrimination task (Figure 3). *Total times* were shortened with a larger number of distractors in the mixed condition,  $F(2, 12) = 9.3, p < .004$ , indicating that strengthened perceptual grouping facilitates focal attention allocation to the target. However, *total times* were independent of distractor numbers in the blocked condition,  $F < 1$ . Single target trials showed overall the shortest total times.

The blocked condition was faster overall than the mixed condition,  $F(1, 6) = 14.82, p < .01$ . Paired comparisons were significant for all distractor cases: 2 distractors ( $p < .002$ ), 5 distractors ( $p < .05$ ), and 11 distractors ( $p < .03$ ). In particular, Maljkovic and Nakayama (1994) explained the

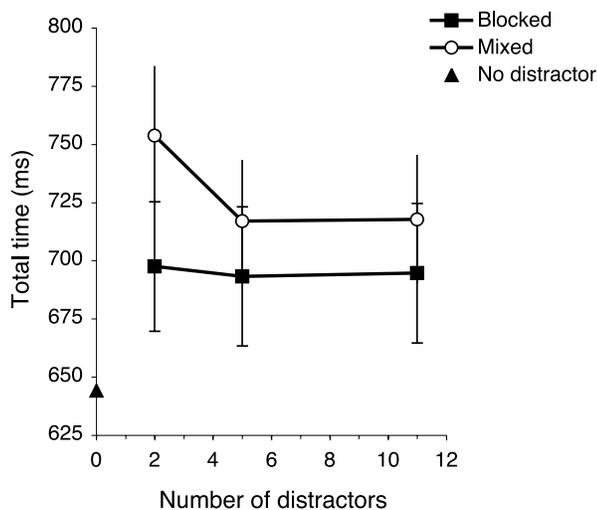


Figure 3. Averaged total times of manual-pointing movements from all participants as a function of the number of distractors. For comparison, the total time of single target trials without distractors is also shown at the extreme left (triangle). Participants showed decreasing total times with larger distractor numbers in the mixed condition, whereas total times were independent of the number of distractors in the blocked condition. In addition, total times of the blocked condition were shorter overall compared to those of the mixed condition. The error bars show the between participants standard errors.

advantage in the blocked condition based on *perceptual priming effect*. The priming effect that facilitates the shift of focal attention to the target can be built up when attended target features are repeated consecutively. We will address this difference between the blocked and mixed conditions in more detail in Experiment 2.

Also an interaction effect between the target color consistency and number of distractors was significant,  $F(2, 12) = 18.3, p < .001$ . There were no speed–accuracy trade-offs in odd-color target selection for all temporal indexes,  $F < 1$ .

Given the fact that we observed similar search patterns in perceptual discrimination (Bravo & Nakayama, 1992), saccades (McPeck et al., 1999), and manual-pointing tasks, we suggest that a qualitatively similar scope of attention is required for both fine feature discrimination and goal-directed manual pointing. It is worth noting that detailed feature discrimination was not required for simple pointing.

To examine the influence of facilitated attention allocation on each segment of visually guided motor behavior, we also divided total time into two components: *initiation latency* and *movement duration* (Figure 4).

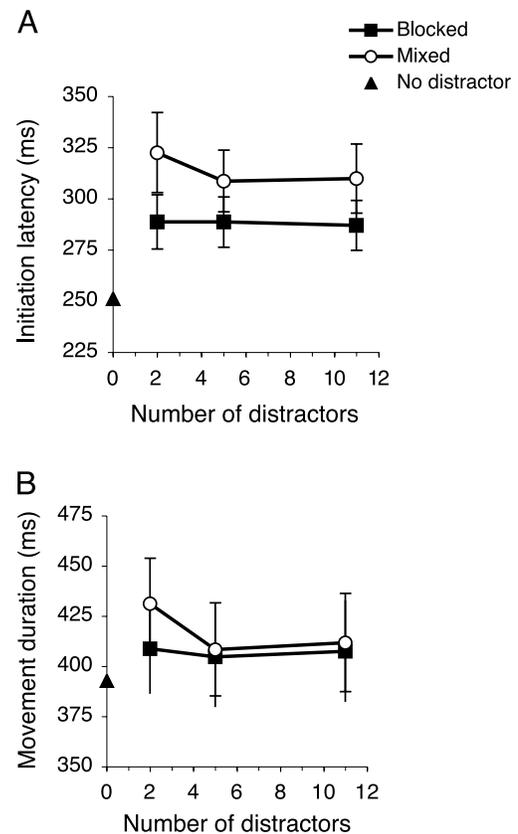


Figure 4. Averaged initiation latency (A) and movement duration (B) of manual pointing from all participants as a function of the number of distractors in the mixed and blocked conditions. For comparison, the result of single target trials without distractors is also shown at the extreme left (triangle). The error bars represent the between participants standard errors.

## (2) Initiation latency and movement duration

Initiation latency (Figure 4A) reflects process before movement onset (Glover, 2004). We observed that patterns of initiation latency were similar to those of total time. The mixed condition showed shortened initiation latency with larger numbers of distractors,  $F(2, 12) = 4.0$ ,  $p < .05$ , whereas the blocked condition showed no effect,  $F < 1$ . Thus, there was a significant interaction effect between the target color consistency and the number of distractors,  $F(2, 12) = 10.1$ ,  $p < .003$ .

Movement duration (Figure 4B) like initiation latency was also shortened with large numbers of distractors only in the mixed condition,  $F(2, 12) = 21.8$ ,  $p < .001$ . Therefore, a significant interaction effect between the target color consistency and the number of distractors was also found,  $F(2, 12) = 7.2$ ,  $p < .01$ .

Comparing the patterns of initiation latency and movement duration, the target feature (color) priming effect was evident mainly in initiation latency. Initiation latency was shorter in the blocked condition than in the mixed condition for all distractor numbers,  $F(1, 6) = 12.78$ ,  $p < .02$ . Paired contrasts were also significant for all distractor cases: 2 distractors ( $p < .008$ ), 5 distractors ( $p < .02$ ), and 11 distractors ( $p < .02$ ). This priming effect in initiation latency may indicate that a part of visual decision is presumably made before the motor plan is in action. However, the decision carried out before movement initiation was not completed. Movement duration still showed a significant difference in two-distractor cases,  $t(6) = 3.7$ ,  $p < .01$ , where distractor–target competition is the strongest. The reason for this difference becomes clarified when examining movement trajectories.

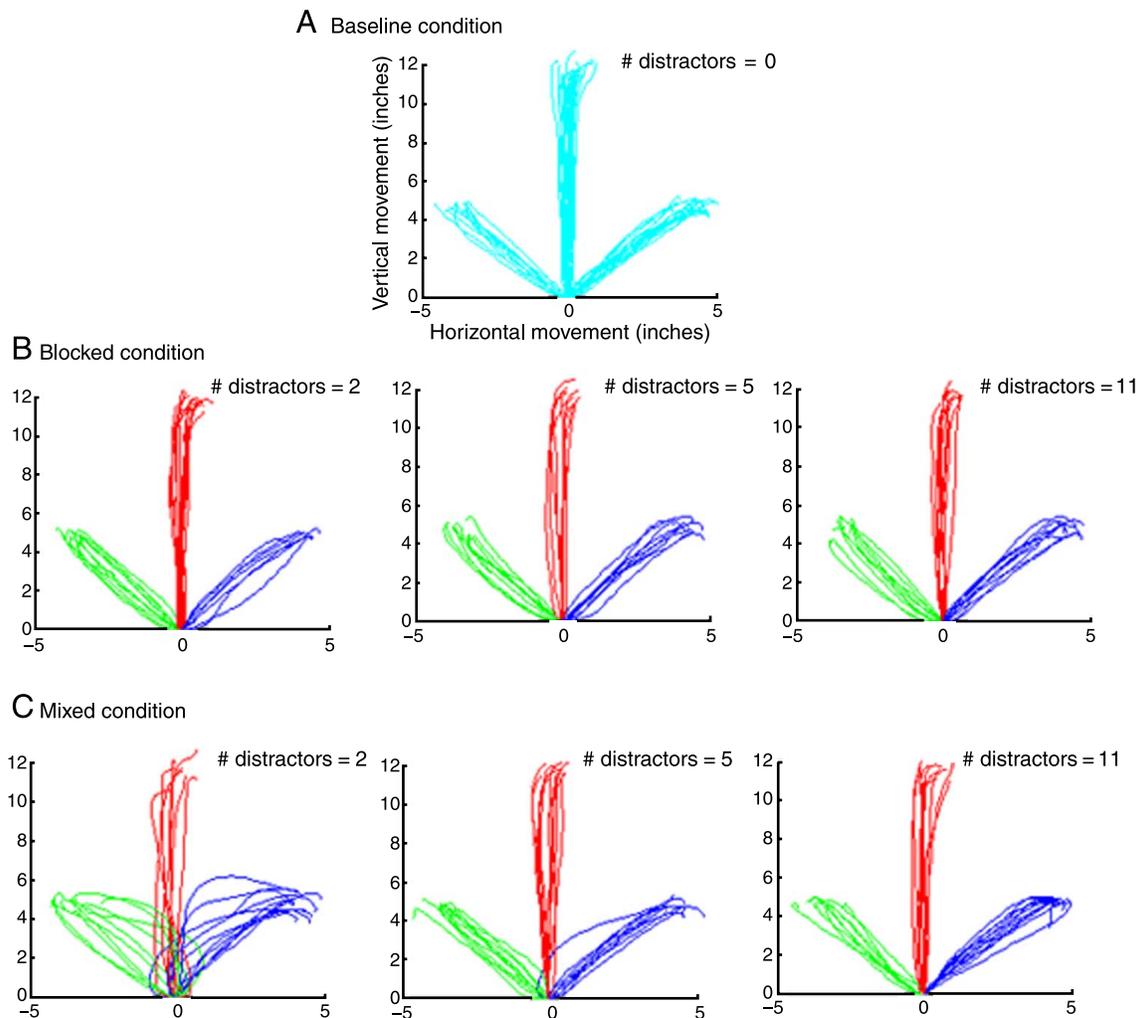


Figure 5. Manual-pointing trajectories to the three target locations from one of the participants. In baseline trials (A), the participant typically made direct movements to each target location. In the blocked (B) and mixed (C) conditions, trajectories associated with each target location are depicted by three distinct colors: green (eight o'clock position), red (twelve o'clock), and blue (four o'clock). These trajectories are three dimensional, but for clarity we only show the X and Y dimensions where the greatest difference between trajectory types is most evident.

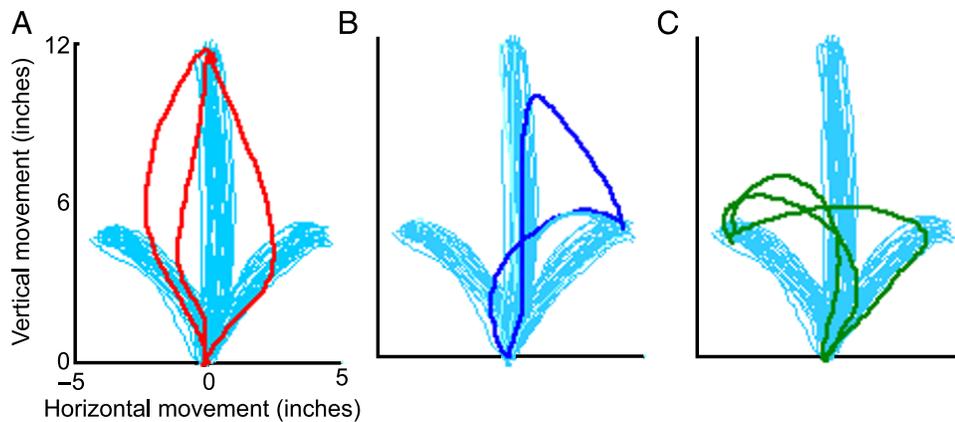


Figure 6. Examples of curved trajectories in the mixed condition two-distractor case (red, green, and blue) in comparison with those of no distractor cases (cyan). This is depicted for odd-colored targets appearing in the center (A), right (B), or left positions (C).

### Manual-pointing trajectories

Given the similarity of visual search patterns in manual-pointing and perceptual discrimination tasks, we argue that focused attention is also involved in manual pointing. How does increasing the number of distractors, facilitating the allocation of focused attention, affect movement trajectories? Shortened visual search time with large numbers indicates that the competition for target selection is reduced although it has been argued that more distractors should increase target uncertainty and interference from distractors (Hick, 1952).

Figure 5 shows examples of hand movement trajectories. As in the single target condition (Figure 5A), movement trajectories were straight in the blocked condition (Figure 5B), as well in the mixed condition with large numbers of distractors. In contrast, many curved trajectories were observed in two-distractor trials of the mixed condition (Figure 5C). In this case, the competition between target and distractors was strong because of relatively weak perceptual grouping. Thus, the magnitude of trajectory curvatures increases due to increasing target–distractor competition rather than due to the simple presence or increasing number of distractors (as would be predicted from Hick’s law, 1952). This also shows that when competing stimuli are presented, goal-directed hand movements can be initiated before the correct target is selected.

This is consistent with results obtained from saccades in humans and in monkeys. These studies have demonstrated that the size and frequency of curved saccades increase as the number of distractors decreases (Arai et al., 2004; McSorley & Findlay, 2003). In particular, curved saccades toward a distractor in the odd-colored target search tasks are accompanied by increased pre-saccadic activity of neurons coding the distractor site in the superior colliculus (SC). Thus, the magnitude of increased activity is correlated with the strength of target–distractor competition (McPeck, Han, & Keller, 2003).

Some examples of typical trajectories shown in Figure 6 demonstrate that early portions of curved trajectories toward the distractor (red, green, and blue) can share the

path with trajectories directed to a given distractor (cyan).<sup>1</sup> This indicates that movements are not randomly made but directed toward distractors. Therefore, we suggest that the initial direction of movement trajectories in our study is also associated with the current location of focused attention.

The similar results obtained for saccades and reaching controlled by distinctive neural mechanisms supports the general role of focused attention. Focused attention is likely to be required for all visually guided motor actions. Also, it implies that the planning of arm movements reflects internal target selection processes over time.

To characterize these initial selection errors, we measured the global trajectory curvature: *maximum curvature*. Overall, larger maximum curvatures were observed in the mixed condition than in the blocked condition (Figure 7),  $F(1, 6) =$

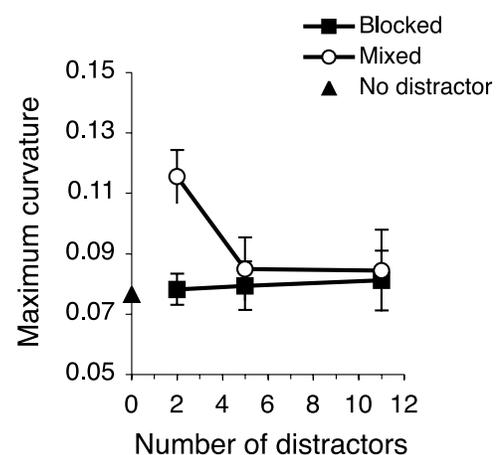


Figure 7. Averaged maximum curvatures from all participants in Experiment 1 as a function of the number of distractors in the mixed and blocked conditions. For comparison, the result of single target trials without distractors is also shown at the extreme left (triangle). The error bars represent the between participants standard errors.

9.8,  $p < .02$ . There was a significant distractor number effect,  $F(2, 12) = 6.3$ ,  $p < .02$ . The interaction effect between target color consistency and distractor numbers was also significant,  $F(2, 12) = 64.1$ ,  $p < .001$ .

Maximum curvatures were significantly reduced with large numbers of distractors in the mixed condition,  $F(2, 12) = 28.5$ ,  $p < .001$ . However, the number of distractors did not affect maximum curvature in the blocked condition,  $F < 1$ . With 5 or 11 distractors, there was no significant difference between maximum curvatures in the blocked and mixed conditions,  $F(1, 6) = 1.2$ ,  $p < 1$ . Thus, it confirmed the impression from trajectories shown in Figure 5. That is, movements were more frequently initiated toward distractors when the perceptual grouping effect was too weak to counteract the competition between target and distractors.

## Experiment 2

In Experiment 1, we concluded that focused attention needs to be allocated to the specific reach target by showing that perceptual grouping facilitates pointing reaction times and reduces trajectory curvatures.

We also showed that manual pointing was faster overall in the blocked condition than in the mixed condition (Figure 3). The advantage in the blocked condition can be explained by the perceptual priming effect. Maljkovic and Nakayama (1994) showed that odd-colored target search times gradually decreased as the number of consecutive same-color target repetitions increased. Saccadic tasks applying the odd-colored target search paradigm also demonstrated the existence of perceptual priming effects in both human and nonhuman primates (Bichot & Schall, 1999; McPeck & Keller, 2001; McPeck et al., 1999).

Thus, it has been suggested that short-term memory of a prior target facilitates focal attention to the current target when both targets share the same attended feature, such as color. The fact that only attended, but not unattended, feature repetitions lead to this perceptual priming effect indicates the critical role of focal attention in this process (Maljkovic & Martini, 2005; Maljkovic & Nakayama, 1994, 1996, 2000). Therefore, if a similar priming effect is observed in manual-pointing tasks, this again would support the idea that directing focal attention to the target is closely associated with goal-directed manual pointing.

In Experiment 2, we manipulated the length of the same-color target repetitions to investigate whether repetitions of the attended target feature (color) lead to a similar priming effect in manual-pointing tasks.

## Methods

The display and procedure of Experiment 2 were essentially the same as in Experiment 1, except that only the two-distractor case was presented because this case showed the

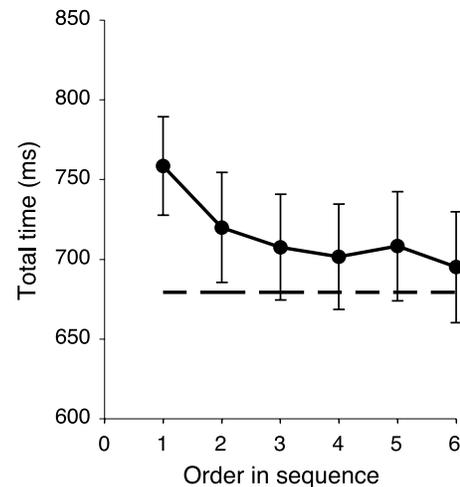


Figure 8. Averaged total time of manual-pointing movements from all participants as a function of the number of same target color repetitions. The error bars represent the between participants standard errors.

largest difference between the blocked and mixed conditions. The length of the run of same-color targets was manipulated.

To generate longer sequences, three different lengths of same-color target runs were used (2, 4, 6 or 3, 5, 6). Each sequence length was randomly presented within a block. Each participant participated in four blocks (96 trials/block). The blocked condition was presented before and after the sequence condition and averaged as a baseline. Each participant experienced all the conditions and repeated ANOVAs were conducted for statistical analysis.

## Results and discussion

### Manual-pointing reaction times

#### (1) Total time

Figure 8 shows *total time* as a function of the number of same target color repetitions. Total time was reduced as the number of same-color target repetitions increased,  $F(5, 30) = 68$ ,  $p < .001$ . For instance, total time decreased between 1 and 2 repetitions,  $t(6) = 7.4$ ,  $p < .001$ , between 2 and 3 repetitions,  $t(6) = 4.5$ ,  $p < .004$ , and between 3 and 6 repetitions,  $t(6) = 2.7$ ,  $p < .05$ .

Only after four to five consecutive same-color target trials did total time reach the baseline level extracted from the blocked condition,  $p < .2$ . This cumulative priming effect again supported the idea that allocation of focal attention to the target is strongly associated with a target selection process for manual-pointing movements. There were no speed–accuracy trade-offs,  $F < 1$ .

#### (2) Initiation latency and movement duration

To scrutinize the influence of facilitated attentional allocation by cumulative priming, we also divided *total time* into *initiation latency* and *movement duration* (Table 1).

Order in sequence	Initial latency (ms)	Movement duration (ms)
1	267 (13)	491 (29)
2	262 (15)	458 (29)
3	257 (17)	451 (29)
4	254 (15)	447 (32)
5	252 (17)	456 (31)
6	248 (15)	447 (32)
Baseline	245 (7)	434 (26)

Table 1. Initiation latencies and movement duration of manual-pointing movements for the number of repetitions.

Both *initiation latency*,  $F(5, 30) = 57.4$ ,  $p < .001$ , and *movement duration*,  $F(5, 30) = 40.4$ ,  $p < .001$ , showed significant cumulative priming effects. There was a significant interaction effect between the two subcomponents of *total time* and the number of repetitions, reflecting slightly different patterns of priming effects,  $F(5, 30) = 6.8$ ,  $p < .001$ . *Initiation latency* was gradually reduced, whereas *movement duration* was shortened the most after one repetition.

### Manual-pointing trajectories

*Initiation latency* and *movement duration* indicate that facilitated focused attention allocation by cumulative priming also facilitates manual pointing to the target. We also analyzed full trajectories of pointing movements to examine the continuous influence of the cumulative priming effect on target selection. As in [Experiment 1](#), we calculated *maximum curvatures* to quantify the magnitude of trajectory curvatures.

*Maximum curvatures* ([Figure 9](#)) showed that repetitions of the target feature not only affect reaction times, but also trajectories. *Maximum curvatures* decreased with target color repetitions,  $F(5, 30) = 39.9$ ,  $p < .001$ . The most noticeable curvature reduction occurred after one repetition, whereas very little change occurred between two and six repetitions.

The largest maximum curvature in the target color switching point (the first in sequence order) is also consistent with results from previous saccadic studies in humans and monkeys although these studies did examine the parametric relationship between the magnitude curvature and priming effect as we did ([McPeck & Keller, 2001](#); [McPeck et al., 1999](#); [McPeck, Skavenski, & Nakayama, 2000](#)). In these studies, when the distractor color on the current trial was strongly primed by previous trials' repeated target color, participants more often made an initial saccade to the distractor. Increased curved trajectories in our study can be also explained by this cumulative priming effect.

In [Experiment 2](#), we again found support for a strong association between focused attention and goal-directed manual pointing because we observed that manual pointing

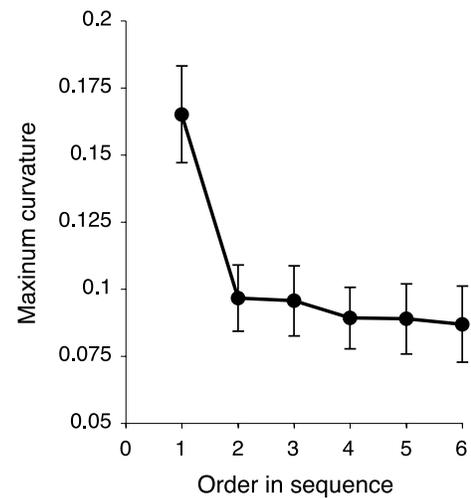


Figure 9. Averaged maximum curvatures as a function of the number of repetitions from all participants in [Experiment 2](#). The error bars show the between participants standard errors.

is facilitated by attended target feature repetitions just as perceptual discrimination ([Maljkovic & Martini, 2005](#); [Maljkovic & Nakayama, 1994, 1996, 2000](#); [McPeck & Keller, 2001](#)) and saccades are ([Bichot & Schall, 1999](#); [McPeck et al., 1999](#)). In addition, we also demonstrated that the cumulative priming effect reduces movement trajectory curvature.

## General discussion

We examined whether localizing a target for manual pointing requires that focused attention be directed to the target. Using odd-colored target search tasks, we showed that manipulations such as increasing perceptual grouping of distractors or increasing cumulative priming effects of target colors facilitate manual pointing and reduces trajectory curvatures. The facilitatory effect is seen not only in *total time* but also in its components such as *initiation latency* and *movement duration*.

Because these manipulations have been shown to facilitate the deployment of narrowly focused attention to a target but not for distributed attention ([Bravo & Nakayama, 1992](#); [Maljkovic & Nakayama, 1994](#)), this adds further support to the view that visually guided actions require attention and specifies the type of attention involved ([Deubel et al., 1998](#); [Kowler et al., 1995](#); [McPeck et al., 1999](#); [Schiegg, Deubel, & Schneider, 2003](#); [Schneider & Deubel, 2002](#); [Tipper et al., 1992](#)).

It is worth noting that simple target-directed pointing mirrors results that can be obtained when a very fine discrimination is required. This implies that coordinating visually guided action to the target requires more than

simple detection or perceptual localization of the target, which can be achieved by a distributed attentional allocation. Instead, the seemingly effortless pointing movements require focused attention as well. In particular, the similarity between the two motor systems controlled by distinctive neural mechanisms supports the general role of focused attention. For instance, as with reaching reaction times, saccadic latencies are also shortened as the number of distractors (McPeck et al., 1999; McSorley & Findlay, 2003) and repetition of attended target features increase (Bichot & Schall, 1999; McPeck & Keller, 2001; McPeck et al., 1999). Also as in the current study, the size and frequency of curved saccades increase as the number of distractors decreases, indicating an overall improvement in performance (Arai et al., 2004; McPeck et al., 2003; McSorley & Findlay, 2003).

The presence of highly curved reaching movement trajectories directed first to a distractor then to the target reflects ongoing changes in focal attentional deployment and target selection. Given the fact that motor plans continuously interact with target–distractor competition even after the movements is initiated, we argue that the hand movement is not a passive carrier of a completed visual decision. Rather it reflects decision-making process over time. Although the view of interactive connection between motor systems and cognitive processes challenges traditional cognitive theories based on the assumption that perception, cognition, and action are distinctive and serially processed domains, it is in accord with recent findings from neurophysiological studies (Cisek, 2005; Shadlen, 2002).

For example, the superior colliculus (SC) traditionally viewed as controlling the mechanical aspects of saccades, is also involved in saccade target selection. McPeck and Keller (2004) demonstrated that while chemical lesions temporarily inactivated just one retinotopic locus in SC, saccades to the target in inactivated field were misdirected to distractors, not simply to intermediate points as would be predicted from a simple vector averaging motor schema for the SC. Carello and Krauzlis (2004) have also shown that when subthreshold microstimulation was applied to the SC while monkeys selected a target for a pursuit or saccade movement, the proportion of selections toward contralateral stimuli to the site of stimulation increased. This contralateral response bias was limited to the initial target location and not the direction of eye movement in pursuit.

Not only the SC, but also the dorsal premotor area (PMd), a structure mainly involved in initiation and execution of limb movements, is also involved in reach target selection. Cisek and Kalaska (2002, 2005) showed in single cell recordings that when two potential targets were presented for selective reaching, the PMd in monkeys generated two simultaneous signals corresponding to each of the directions of movement of two targets during a delay period. This suggests that the PMd can represent multiple action plans concurrently, even before cognitive decision is made for

the correct target. Taken together, these results demonstrate the direct role of SC and PMd in higher level target selection and decision making as well as motor control, supporting the notion that actions directed toward a goal are not mere reflections of completed cognitive processes.

Since Woodworth (1899), numerous studies have shown that participants can make rapid online corrective movements, particularly when movement correction to a single target is required. For example, participants can amend an ongoing movement with short latency relying on proprioceptive or visual feedback when a target location is displaced in a small degree regardless of their awareness about changes (Brenner & Smeets, 1997; Goodale, Pelisson, & Prablanc, 1986; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983; van Sonderen, Denier van der Gon, & Gielen, 1988).

In the current study, we have also observed efficient movement correction although a large degree of movement adjustment and an additional step of target re-selection were required. Our subsequent study (Song & Nakayama, 2005) demonstrated that this efficient trajectory correction in our paradigm is because two motor plans for competing stimuli can be processed simultaneously. One possible neural structure for this concurrent processing for competing reach plans would be PMd, where multiple reach targets can be encoded (Cisek & Kalaska, 2002, 2005).

Our results also indicate that allocation of focal attention is commonly critical for perceptual discrimination, saccades, and reaching (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; McPeck et al., 1999). Although neuropsychological patients (Goodale & Milner, 1992; Milner & Goodale, 1995; Stoerig & Cowey, 1997) and normal participants (Aglioti, DeSouza, & Goodale, 1995; Haffenden & Goodale, 1998) have shown functional and anatomical dissociation between visual perception and spatial-motor action, it does not rule out that under normal circumstances, these processes are typically synchronized (Humphreys et al., 2004).

Recent neuroimaging and single-cell recording studies have demonstrated the overlap between overt and covert attentional networks in frontal and parietal lobes (for reviews, see Corbetta & Shulman, 2002; Kanwisher & Wojciulik, 2000; Moore, 2006). For instance, Moore and Fallah (2004) showed that when saccadic preparation is evoked by microstimulating the frontal eye field (FEF), visual detection at the stimulated site is enhanced. Microstimulation of the SC also led to similar results such as improving change detection (Cavanaugh & Wurtz, 2004) and lowering motion coherence detection threshold (Müller, Philiastides, & Newsome, 2005). Functional magnetic resonance imaging (fMRI) study has also demonstrated the regional overlap between covert attentional and saccadic shifts (Corbetta et al., 1998; Culham et al., 1998; Nobre, Gitelman, Dias, & Mesulam, 2000).

Yet, the question of whether attention for perception and attention for action are distinct or unitary still remains.

Perceiving objects and executing motor responses to them often co-occur. In addition, the objects of our actions are the ones that are usually attended. Thus, two separate but parallel mechanisms could exist and operate flawlessly in everyday life because they are customarily coupled. Alternatively, there could be just one attention mechanism sharing the limited resource between perception and action (Kahneman, 1973; Norman & Bobrow, 1975). These two conjectures are very different at the level of mechanisms and suggest different architectures linking perception and motor systems.

Another contribution of the current study is to demonstrate on-line interaction between visual attention and goal-directed movements over time, an opportunity not afforded by the usual discrete responses used in typical perceptual and cognitive tasks. Thus, a continuous manual-pointing task can be potentially useful for studies on online cognitive or perceptual competition processes. Instead of inferring intermediate cognitive processes based on the final reaction times, action tasks can provide information about internal states as they unfold over time. Spivey, Grosjean, and Knoblich (2005) also made the similar point in their study of language production.

## Conclusions

In this study, we demonstrate that any manipulations that facilitate allocation of focal attention also speed manual-pointing movements. We argue that *focused* attention rather than *distributed* attention is involved in simple goal-directed pointing. Our results are consistent with results from previous perceptual discrimination and saccadic studies. Taken together, they underscore the importance of focal attention, not only for perception, but for visually guided actions.

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## Footnote

<sup>1</sup>When multiple stimuli are presented, saccadic and reaching trajectories either curved *toward* (Arai et al., 2004; McPeck & Keller, 2001; McPeck et al., 2003) or away from distractors (McSorley & Findlay, 2003; McSorley, Haggard, & Walker, 2004; Tipper et al., 1998) have been observed.

Recently, Walker, Haggard, & McSorley (2006) reported in saccadic tasks that trajectories are typically curved *toward* distractors, reflecting target-distractor competition when a target location is unpredictable as in the current study. Yet, trajectories are typically *away* from distractors, reflecting distractor inhibition when the target location is specified in advance such as by *precue*.

## References

- Aglioti, S., DeSouza, J. F., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology*, *5*, 679–685. [[PubMed](#)] [[Article](#)]
- Allport, A. (1987). Selection for action: Some behavioural and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action*. Hillsdale, NJ: Erlbaum.
- Allport, A. (1993). Attention and control: Have we been asking the wrong questions? In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XI: V*. Cambridge, MA: MIT Press.
- Arai, K., McPeck, R. M., & Keller, E. L. (2004). Properties of saccadic responses in monkey when multiple competing visual stimuli are present. *Journal of Neurophysiology*, *91*, 890–900. [[PubMed](#)] [[Article](#)]
- Atkeson, C. G., & Hollerbach, J. M. (1985). Kinematic features of unrestrained vertical arm movements. *Journal of Neuroscience*, *5*, 2318–2330. [[PubMed](#)] [[Article](#)]
- Atkinson, J., & Braddick, O. J. (1989). ‘Where’ and ‘what’ in visual search. *Perception*, *18*, 181–189. [[PubMed](#)]
- Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences*, *20*, 723–767. [[PubMed](#)]
- Bergen, J. R., & Julesz, B. (1983). Parallel versus serial processing in rapid pattern discrimination. *Nature*, *303*, 696–698. [[PubMed](#)]
- Bichot, N. P., & Schall, J. D. (1999). Effects of similarity and history on neural mechanisms of visual selection. *Nature Neuroscience*, *2*, 549–554. [[PubMed](#)] [[Article](#)]

- Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics*, *51*, 465–472. [PubMed]
- Brenner, E., & Smeets, J. B. (1997). Fast responses of the human hand to changes in target position. *Journal of Motor Behavior*, *29*, 297–310. [PubMed]
- Carello, C. D., & Krauzlis, R. J. (2004). Manipulating intent: Evidence for a causal role of the superior colliculus in target selection. *Neuron*, *43*, 575–583. [PubMed] [Article]
- Castiello, U. (1999). Mechanisms of selection for the control of hand action. *Trends in Cognitive Sciences*, *3*, 264–271. [PubMed]
- Cavanaugh, J., & Wurtz, R. H. (2004). Subcortical modulation of attention counters change blindness. *Journal of Neuroscience*, *24*, 11236–11243. [PubMed] [Article]
- Cisek, P. (2005). Neural representations of motor plans, desired trajectories, and controlled objects. *Cognitive Processing*, *6*, 15–24.
- Cisek, P., & Kalaska, J. F. (2002). Simultaneous encoding of multiple potential reach directions in dorsal premotor cortex. *Journal of Neurophysiology*, *87*, 1149–1154. [PubMed] [Article]
- Cisek, P., & Kalaska, J. F. (2005). Neural correlates of reaching decisions in dorsal premotor cortex: Specification of multiple direction choices and final selection of action. *Neuron*, *45*, 801–814. [PubMed] [Article]
- Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron*, *21*, 761–773. [PubMed] [Article]
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews: Neuroscience*, *3*, 201–215. [PubMed]
- Culham, J. C., Brandt, S. A., Cavanagh, P., Kanwisher, N. G., Dale, A. M., & Tootell, R. B. (1998). Cortical fMRI activation produced by attentive tracking of moving targets. *Journal of Neurophysiology*, *80*, 2657–2670. [PubMed] [Article]
- Desmurget, M., Jordan, M., Prablanc, C., & Jeannerod, M. (1997). Constrained and unconstrained movements involve different control strategies. *Journal of Neurophysiology*, *77*, 1644–1650. [PubMed] [Article]
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*, 1827–1837. [PubMed]
- Deubel, H., Schneider, W. X., & Paprotta, I. (1998). Selective dorsal and ventral processing: Evidence for a common attentional mechanism in reaching and perception. *Visual Cognition*, *5*, 81–107.
- Folk, C. L., & Egeth, H. (1989). Does the identification of simple features require serial processing? *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 97–110. [PubMed]
- Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences*, *27*, 3–24. [PubMed]
- Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neuroscience*, *15*, 20–25. [PubMed]
- Goodale, M. A., Pélisson, D., & Prablanc, C. (1986). Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. *Nature*, *320*, 748–750. [PubMed]
- Green, M. (1992). Visual search: Detection, identification, and localization. *Perception*, *21*, 765–777. [PubMed]
- Haffenden, A. M., & Goodale, M. A. (1998). The effect of pictorial illusion on prehension and perception. *Journal of Cognitive Neuroscience*, *10*, 122–136. [PubMed]
- Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *4*, 11–26.
- Humphreys, G. W., Riddoch, M. J., Linnell, K. J., Punt, D., Edwards, M. G., & Wing, A. M. (2004). Attending to what you are doing: Neuropsychological and experimental evidence for interactions between perception and action. In G. W. Humphreys & M. J. Riddoch (Eds.), *Attention in action*. London: Psychology Press.
- Jeannerod, M. (1988). *The neural and behavioural organization of goal-directed movements*. Oxford: Clarendon Press.
- Johnston, J. C., & Pashler, H. (1990). Close binding of identity and location in visual feature perception. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 843–856. [PubMed]
- Julesz, B. (1986). Texton gradients: The Texton theory revisited. *Biological Cybernetics*, *54*, 245–251. [PubMed]
- Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, New Jersey: Prentice-Hall.
- Kanwisher, N., & Wojciulik, E. (2000). Visual Attention: Insights from Brain Imaging. *Nature Reviews Neuroscience*, *1*, 91–100. [PubMed]
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, *4*, 219–227. [PubMed]
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*, 1897–1916. [PubMed]

- Kristjansson, A., Mackeben, M., & Nakayama, K. (2001). Rapid, object-based learning in the deployment of transient attention. *Perception, 30*, 1375–1387. [[PubMed](#)]
- Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research, 41*, 3559–3565. [[PubMed](#)]
- Land, M. F., & McLeod, P. (2000). From eye movements to actions: How batsmen hit the ball. *Nature Neuroscience, 3*, 1340–1345. [[PubMed](#)] [[Article](#)]
- Maljkovic, V., & Martini, P. (2005). Implicit short-term memory and event frequency effects in visual search. *Vision Research, 45*, 2831–2846. [[PubMed](#)]
- Maljkovic, V., & Nakayama, K. (1994). Priming of popout: I. Role of features. *Memory & Cognition, 22*, 657–672. [[PubMed](#)]
- Maljkovic, V., & Nakayama, K. (1996). Priming of popout: II. The role of position. *Perception & Psychophysics, 58*, 977–991. [[PubMed](#)]
- Maljkovic, V., & Nakayama, K. (2000). Priming of Popout: III. A short-term implicit memory system beneficial for rapid target selection. *Visual Cognition, 7*, 571–595.
- Marr, D. (1980). Visual information processing: The structure and creation of visual representations. *Philosophical Transactions of the Royal Society of London: Series B, Biological Sciences, 290*, 199–218. [[PubMed](#)]
- McPeck, R. M., Han, J. H., & Keller, E. L. (2003). Competition between saccade goals in the superior colliculus produces saccade curvature. *Journal of Neurophysiology, 89*, 2577–2590. [[PubMed](#)] [[Article](#)]
- McPeck, R. M., & Keller, E. L. (2001). Short-term priming, concurrent processing, and saccade curvature during a target selection task in the monkey. *Vision Research, 41*, 785–800. [[PubMed](#)]
- McPeck, R. M., & Keller, E. L. (2004). Deficits in saccade target selection after inactivation of superior colliculus. *Nature Neuroscience, 7*, 757–763. [[PubMed](#)]
- McPeck, R. M., Maljkovic, V., & Nakayama, K. (1999). Saccades require focal attention and are facilitated by a short-term memory system. *Vision Research, 39*, 1555–1566. [[PubMed](#)]
- McPeck, R. M., Skavenski, A. A., & Nakayama, K. (2000). Concurrent processing of saccades in visual search. *Vision Research, 40*, 2499–2516. [[PubMed](#)]
- McSorley, E., & Findlay, J. M. (2003). Saccade target selection in visual search: Accuracy improves when more distractors are present. *Journal of Vision, 3*(11), 877–892, <http://journalofvision.org/3/11/20/>, doi:10.1167/3.11.20. [[PubMed](#)] [[Article](#)]
- McSorley, E., Haggard P., & Walker, R. (2004). Distractor modulation of saccade trajectories: Spatial separation and symmetry effects. *Experimental Brain Research, 155*, 320–333. [[PubMed](#)]
- Milner, A. D., & Goodale, M. A. (1995). *The visual brain in action*. Oxford: Oxford University Press.
- Moore, T. (2006). The neurobiology of visual attention: Finding sources. *Current opinions in neurobiology, 16*, 159–165. [[PubMed](#)]
- Moore, T., & Fallah, M. (2004). Microstimulation of the frontal eye field and its effects on covert spatial attention. *Journal of Neurophysiology, 91*, 152–162. [[PubMed](#)] [[Article](#)]
- Müller, J. R., Philiastides, M. G., & Newsome, W. T. (2005). Microstimulation of the superior colliculus focuses attention without moving the eyes. *Proceedings of the National Academy of Sciences of the United States of America, 102*, 524–529. [[PubMed](#)] [[Article](#)]
- Nakayama, K. (1990). The iconic bottleneck and the tenuous link between early visual processing and perception. In C. Blakemore (Ed.), *Vision: Coding and efficiency*. Cambridge University Press.
- Nakayama, K., & Joseph, J. S. (1998). Attention, pattern recognition and popout in visual search. In R. Parasuraman (Ed.), *The Attentive Brain*. Cambridge, MA: MIT Press.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*, 1631–1647. [[PubMed](#)]
- Neggers, S. F., & Bekkering, H. (2000). Ocular gaze is anchored to the target of an ongoing pointing movement. *Journal of Neurophysiology, 83*, 639–651. [[PubMed](#)] [[Article](#)]
- Neggers, S. F., & Bekkering, H. (2002). Coordinated control of eye and hand movements in dynamic reaching. *Human Movement Science, 21*, 349–376. [[PubMed](#)]
- Neumann, O. (1987). Beyond capacity: A functional view of attention. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on Perception and Action*. Hillsdale, NJ: Erlbaum.
- Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice Hall.
- Nobre, A. C., Gitelman, D. R., Dias, E. C., & Mesulam, M. M. (2000). Covert visual spatial orienting and saccades: Overlapping neural systems. *NeuroImage, 11*, 210–216. [[PubMed](#)]
- Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource limited processes. *Cognitive Psychology, 7*, 44–64.
- Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

- Pashler, H. (1998). *The Psychology of Attention*. Cambridge, MA: MIT Press.
- Prablanc, C., & Martin, O. (1992). Automatic control during hand reaching at undetected two-dimensional target displacements. *Journal of Neurophysiology*, *67*, 455–469. [PubMed]
- Pratt, J., Shen, J., & Adam, J. (2004). The planning and execution of sequential eye movements: Saccades do not show the one target advantage. *Human Movement Science*, *22*, 679–688. [PubMed]
- Sagi, D., & Julesz, B. (1985a). Detection versus discrimination of visual orientation. *Perception*, *13*, 619–628. [PubMed]
- Sagi, D., & Julesz, B. (1985b). “Where” and “what” in vision. *Science*, *228*, 1217–1219. [PubMed]
- Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in Motor Behavior*. Amsterdam: North Holland.
- Schall, J. D., & Thompson, K. G. (1999). Neural selection and control of visually guided eye movements. *Annual Review of Neuroscience*, *22*, 241–259. [PubMed]
- Schiegg, A., Deubel, H., & Schneider, W. X. (2003). Attentional selection during preparation of prehension movements. *Visual Cognition*, *10*, 409–431.
- Schneider, W. X., & Deubel, H. (2002). Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: A review of recent findings and new evidence from stimulus-driven saccade control. In W. Prinz & B. Hommel (Eds.), *Attention and Performance: XIX. Common Mechanisms in Perception and Action*. Oxford: Oxford University Press.
- Shadlen, M. N. (2002). Pursuing commitments. *Nature Neuroscience*, *5*, 819–821. [PubMed] [Article]
- Smit, A. C., & Van Gisbergen, J. A. (1990). An analysis of curvature in fast and slow human saccades. *Experimental Brain Research*, *81*, 335–345. [PubMed]
- Soechting, J. F., & Lacquaniti, F. (1983). Modification of trajectory of a pointing movement in response to a change in target location. *Journal of Neurophysiology*, *49*, 548–564. [PubMed]
- Song, J.-H., & Nakayama, K. (2005). Selecting and pointing: Consecutive serial processing? [Abstract]. *Journal of Vision*, *5*(8), 384a, <http://journalofvision.org/5/8/384/>, doi:10.1167/5.8.384.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*, 1–29.
- Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences*, *102*, 10393–10398. [PubMed] [Article]
- Sternberg, S. (1969). The discovery of processing stages. *Acta Psychologica*, *30*, 276–315.
- Stoerig, P., & Cowey, A. (1997). Blindsight in man and monkey. *Brain*, *120*, 535–559. [PubMed] [Article]
- Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature*, *381*, 520–522. [PubMed]
- Tipper, S. P., Howard, L. A., & Houghton, G. (1998). Action-based mechanisms of attention. *Philosophical Transactions of the Royal Society of London: Series B, Biological Sciences*, *353*, 1385–1383. [PubMed] [Article]
- Tipper, S. P., Lortie, C., & Baylis, G. C. (1992). Selective reaching: Evidence for action-centered attention. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 891–905. [PubMed]
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136. [PubMed]
- van Sonderen, J. F., Denier van der Gon, J. J., & Gielen, C. C. (1988). Conditions determining early modification of motor programmes in response to changes in target location. *Experimental Brain Research*, *71*, 320–328. [PubMed]
- Walker, R., McSorley, E., & Haggard, P. (2006). The control of saccade trajectories: Direction of curvature depends on prior knowledge of target location and saccade latency. *Perception & Psychophysics*, *68*, 129–138. [PubMed]
- Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Monographs*, *3*, 1–119.