

Target selection in visual search as revealed by movement trajectories

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Abstract

We examined target selection for visually guided reaching movements in visual search, in which participants reached to an odd-colored target presented with two homogenous distractors. The colors of the target and distractors were randomly switched for each trial between red and green, and the location of the target was varied. Therefore either color could be a distractor or target, and the identity was resolved by grouping two distractors having the same color. Thus, there was ongoing competition between a target and distractors. In some trials, reaches were directed to the target, and in other trials, reaches were initially directed towards a distractor and corrected in mid-flight, showing highly curved trajectories. Interestingly, trials with highly curved trajectories were no less efficient in terms of accuracy or total time. The extra time taken up in movement duration was offset by shorter initial latencies. By analyzing curved trajectories, we demonstrated that corrective movements occur shortly after the onset of initial movement, suggesting that a corrective new target is selected even before initial movement is executed. This provides an explanation as to why misdirected reaches, hastily initiated, can be corrected with minimal loss in overall efficiency. In addition, our results show that the details of movement trajectories allow us to visualize the dynamics of target selection as they unfold in time.

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Keywords: Visual search; Concurrent processing; Visually guided reaching; Curved trajectory; Target selection

1. Introduction

One of the most important functions of the visual system is guiding actions in order to interact with the external world (Abrams, Meyer, & Kornblum, 1990; Carlton, 1981; Hansen & Skavenski, 1977; Hansen & Skavenski, 1985; Keele & Posner, 1968; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Prablanc, Echallier, Jeannerod, & Komilis, 1979; Prablanc, Pelisson, & Goodale, 1986). Visually guided goal-directed actions are often executed in complex and crowded visual scenes, where several different objects compete for attention and action. Previous studies have provided valuable information about how a target is selected for reaches in the presence of competing stimuli. These studies have shown that movement trajectory and kinematics are affected by the presence of distractors, and also by the spatial layout

of the target and distractors (Chang & Abrams, 2004; Fischer & Adam, 2001; Keulen, Adam, Fischer, Kuipers, & Jolles, 2002; Keulen, Adam, Fischer, Kuipers, & Jolles, 2004; Meegan & Tipper, 1998; Song & Nakayama, 2006; Song & Nakayama, 2007a; Song & Nakayama, 2007b; Tipper, Howard, & Houghton, 1998; Tipper, Lortie, & Baylis, 1992; Welsh & Elliott, 2004; Welsh & Elliott, 2005).

For instance, Tipper and colleagues (1992, 1998) demonstrated that when participants reach for a pre-specified target by a color, their reaching trajectories swerve away from distractors. Welsh and Elliott (2005) demonstrated that when the distractor was presented at the precued location while the target was presented at an uncued location, reaction times and trajectory deviations towards the location of the distractor increased. In these studies, a feature to distinguish a relevant target from an irrelevant distractor for an action is typically pre-determined, and a distractor is irrelevant for the task and should be ignored.

However, Song and Nakayama (2006, 2007a, 2007b) have recently modified a visual search paradigm (Bravo

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& Nakayama, 1992) to investigate target selection for reach, in which a target feature can unpredictably vary from trial to trial, and information from distractors is essential for target selection. In this paradigm, an odd-colored target is presented in an array of homogenous distractors, and participants are asked to reach to touch the target. The colors of target and distractors are randomly switched between red and green for each trial so that either color could be a target. The identity of a color stimulus is only resolved by grouping the two distractors having the same color; hence there is ongoing competition between the target and distractors. Perceptual grouping of distractors is facilitated when a greater number of homogeneous distractors are presented. Thus, as the number of distractors increases, reaches are executed and completed faster (Song & Nakayama, 2006; Song, Takahashi, & McPeck, 2008). Improved reach performance with more distractors seems counterintuitive, but in fact, is in accord with bottom-up models of target selection (Julesz, 1986; Koch & Ullman, 1985).

In contrast, a different reach target selection mechanism is involved when the colors of the target and distractors are constant across trials (Song & Nakayama, 2006). Because previous and current trials share the same attended target color in this condition, priming of the previous target color facilitates the rapid deployment of attention directly to an odd-colored target. This priming, mediated by a short-term memory system, is more efficient than bottom-up perceptual grouping process to guide attention, which has been also seen for saccade target selection in humans and monkeys (Bichot & Schall, 2002; McPeck & Keller, 2001; McPeck, Maljkovic, & Nakayama, 1999), and for shifts of attention in humans (Maljkovic & Nakayama, 1994).

Thus, these previous studies indicate that the color-oddity search becomes most difficult when the target is presented with the fewer number of homogenous distractors, and the colors of target and distractors are randomly switched in each trial. In this case, the information from distractors is essential for target selection, imposing an inevitable internal competition between a target and distractors, and where the small number of distractors renders perceptual grouping less efficient (Arai, McPeck, & Keller, 2004; Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; McPeck & Keller, 2001; McPeck et al., 1999; McSorley & Findlay, 2003; Song & Nakayama, 2006; Song et al., 2008).

In the current study, we examined how efficiently competition between reach target and distractor is resolved over time in a color-oddity search task by analyzing curved trajectories initially directed to a distractor and redirected to the target. In particular, to increase target selection competition, we randomly switched the colors of target and distractors between red and green in each trial, and presented only two distractors. Song and Nakayama (2006) showed that when the target were switched from the previous trials, reaches were more often initially directed to a distractor, and then corrected to the target in mid-flight

than remained constant. This indicates that there is a strong initial competition between target and distractors, which is resolved over the time course.

Compared to discrete responses such as button presses, the analysis of continuous overt behaviors has the advantage of allowing internal temporal target selection processes to be mapped onto a visible 3D spatial space. Previous studies have demonstrated that reach trajectories reveal the current locus of focal attention (Song & Nakayama, 2006), as well as revealing subconscious competitions in motor programs (Finkbeiner, Song, Nakayama, & Caramazza, 2008), and decision-making for other higher level cognitive processes (Boulenger, Roy, Paulignan, Deprez, Jeannerod & Nazir, 2006; Song & Nakayama, 2008; Spivey, Grosjean, & Knoblich, 2005). Furthermore, a reach movement can be planned and executed in parallel without substantial delays, while the other movement is processed. Thus, reaching trajectories could also demonstrate timely overlapped target selection processes (e.g. Cisek & Kalaska, 2005; Georgopoulos, Kalaska, & Massey, 1981; Tipper, Howard, & Houghton, 2000; Welsh & Elliott, 2005).

To maximize the visibility of internal target selection processes via movement trajectories, we also intermixed single target trials without distractors (Fig. 1B), and color-oddity search trials (Fig. 1A). Song and Nakayama (2007a) demonstrated that reaches are initiated much faster when relatively easy single target trials are randomly mixed together within a block compared to search trials alone. The presence of such fast responses increase the probability that reach movements will be initiated before target selection is fully resolved.

2. Methods

2.1. Participants

Harvard University students participated for course credit. They were all right-handed with normal color vision and normal visual acuity. Eight participants participated in the visual search experiment, and five new participants participated in the double-step experiment.

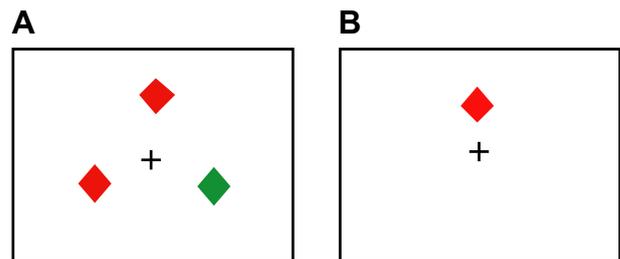


Fig. 1. Schematic diagram of an odd-colored target trial (A), and single target trial (B). In odd-colored target trials, the odd-colored target is presented with two distractors. In single target trials, a lone target is presented without distractors.

2.2. Stimuli

The solid, red or green colored diamond-shaped stimuli ($1.5^\circ \times 1.5^\circ$) were presented against a black background. The red and green were approximately equiluminant using a flicker photometry. The stimuli were arranged uniformly around an imaginary circle with a radius of 12.5° (10.5 cm) from the center of the screen.

2.3. Task

Participants were tested individually in a semi-darkened room. They were seated 48 cm in front of the visual display. In the color-oddy search experiment, there were two types of trials, which were randomly intermixed: odd-colored target and single target trials. In odd-colored target trials (Fig. 1A), the odd-colored target was presented with two distractors. In single target trials (Fig. 1B), a single target was presented without distractors, which was used as baseline for comparison. Participants completed two blocks of trials (96 trials per block) in which odd-colored and single target trials were randomly and equally mixed. Participants were asked to reach for and touch a lone or odd-colored target with their index finger as quickly as possible. The target colors were randomly changed between red and green for each trial. In the odd-colored trials, if the target was red then the distractors were green, and vice-versa. The target was positioned randomly from trial to trial at one of three possible positions, corresponding to 4, 8, and 12 o'clock from the center fixation mark.

In the double-step experiment, we presented only single target trials but in a random fraction of trials (35%), the initial target location was displaced to another of the two possible locations after pre-specified random intervals (150, 200 or 250 ms). Three possible target locations were the same as in the search experiment. At the beginning of each trial for both experiments, a black screen with a white fixation point was presented for 700–900 ms. Then the stimulus display was presented on the screen until participants responded. When participants touched the target within a pre-specified radius of error (0.75° surrounding the target), different beeps were given depending on whether participants touched the correct target or distractor. The intertrial interval was 1000 ms.

2.4. Measuring hand movements

Hand movements were measured with a Fastrak electromagnetic position and orientation measuring system (Polhemus Inc., Colchester, VT) with a sampling rate of 120 Hz. The small position-tracking sensor ($2.26 \times 1.27 \times 1.14$ cm) was attached on the index fingertip of the right hand. The starting position marker (3×3 cm) was approximately aligned with the body midline and 20 cm in front of the participant, on the table. Participants were required to put their index finger on the starting position to initiate each trial. The tracking system was calibrated prior to each block with nine points on the screen.

2.5. Data analysis

Movement data were transmitted to a Power Mac G4 by Vision Shell library for off-line analysis to identify the onset and offset of movements. Hand velocity above or below a threshold of 10 cm/s demarcated the onset and the offset of a movement, respectively. Each trajectory was visually inspected to verify the appropriateness of this criterion. 3D position traces were filtered with a low-pass filter (cutoff frequency of 25 Hz).

Only trials in which participants touched the correct target were included in further analyses. *Initial latency* was defined as the interval between stimulus and movement onset. *Movement duration* was the interval between movement onset and offset. *Total time* was the sum of *initial latency* and *movement duration*. Trials in which initial latencies were below 100 ms or total times were in excess of 1500 ms were excluded as anticipatory movements and outliers. Less than 2% of the trials were removed by target selection errors or latency criteria, which was approximately 2–3 trials per participant.

3. Results

We conducted repeated ANOVAs to examine whether target colors (red and green), and target locations (4, 8, and 12 o'clock) affected search performance. We found that there were no significant main effects of target colors, and positions on temporal measurements (initiation latency, movement duration, and total time), and accuracy. Also, there were no significant interaction effects ($p > .17$). Thus, we collapsed the data across target colors and positions for further analysis.

3.1. Curved trajectories to the target among competing distractors

Fig. 2A demonstrates reach trajectories obtained from the single target trials. The trajectories were straight and the variation between them was small. However, for the odd-colored target case, the results were very different as shown in Fig. 2B. Similar to what has been seen in previous studies using a similar visual search task for reaches (Song & Nakayama, 2006, 2007a, 2007b; Song et al., 2008), the hand frequently moved toward one of the distractors and then curved toward the correct target. These curved trajectories are not simply due to the mere presence of distractors. Previous studies have shown that even with multiple distractors, movement trajectories are straight when the target selection competition is weakened by keeping the colors of the target and distractors constant across trials (McPeck & Keller, 2001; Song & Nakayama, 2006).

As seen in Fig. 2B, the corrective movements are not small adjustments insofar as they require a target re-selection. Thus it seems reasonable to expect that this correction in search trials should be costly. In order to examine the issue of “costs in time”, we separated odd-colored target trials into those including curved and straight trajectories. To classify curved trajectories, in single target trials (Fig. 2A), we first averaged horizontal movement positions towards each target for each participant as the baseline because the horizontal positions of three targets were distinguished from each other. Then we calculated one-and-a-half standard deviations around each average trajectory as depicted in Fig. 3. Trajectories in search trials that crossed this boundary were defined as curved trajectories.

This analysis only included curved trajectories showing a clear indication of correction, that is, trajectories that at the beginning were clearly directed toward one of the three stimuli, but later deviated from it. From 21% to 42% (average 33%) of odd-colored target trials from each participant had clear corrective movements according to this criterion. There was no difference in the number of trials with curved trajectory for each target location, $F < 1$.

Then, we compared mean initial latency, mean movement duration, and mean total time between search trials with straight trajectories and those with curved trajectories. We found that overall, there appears to be no additional time cost in curved trajectory trials in terms of *total time*

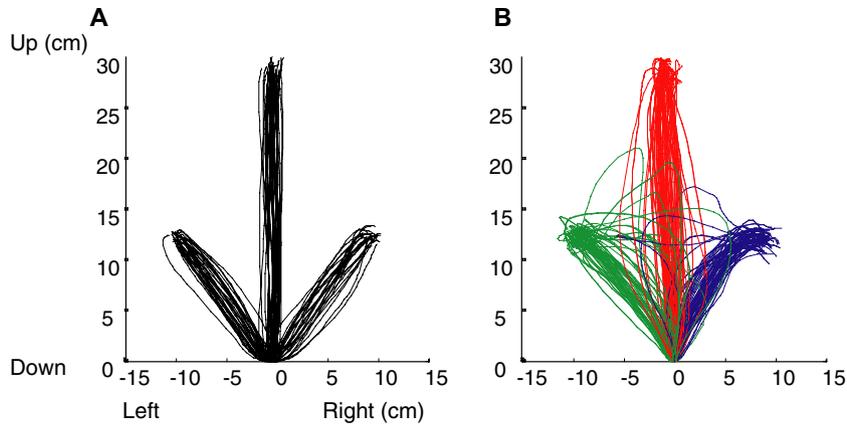


Fig. 2. Movement trajectories to the three target locations from one of the participants. In baseline single target trials (A), the participant typically made direct movements to each target location. In the odd-colored target trials (B), trajectories associated with each target location are depicted by three distinct colors: green (8 o'clock position), red (12 o'clock), and blue (4 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.

(Fig. 4), $t < 1$. The details of the timing of various events indicate that *initial latencies* of trials showing straight trajectories were longer than those of trials showing curved trajectories, $t(7) = 3.9, p < .006$, but *movement duration* for curved trajectories was longer, showing the opposite pattern, $t(7) = 4.1, p < .005$. Thus, recognizing that the total time is the sum of these opposite effects, the total time cost of planning corrective movements is negligible.

Furthermore, this result was not due to speed-accuracy trade-offs. Final target selection accuracy was over 98% in both categories, $F < 1$. To further examine effects of curved trajectories on reach accuracies, we calculated reach endpoint error, and precision in both horizontal and verti-

cal directions for each target location. Reach endpoint error was defined as the distance from the center of a given target, and precision was defined as a variance of reach endpoints in a given target condition.

We conducted $3(\text{target position}) \times 2(\text{trajectory curve})$ repeated ANOVAs for each accuracy and precision index (horizontal reach error, vertical reach error, horizontal precision, and vertical precision). Since there were no main effects and interaction effects of target position in all indexes ($ps .34-.82$), we collapsed all the target positions. Mean horizontal error was .57 cm [.16 (SE)] for trials with straight trajectories, and .68 cm (.16) for trials with curved trajectories, $F(1, 7) = .13, p = .67$. Mean vertical error was

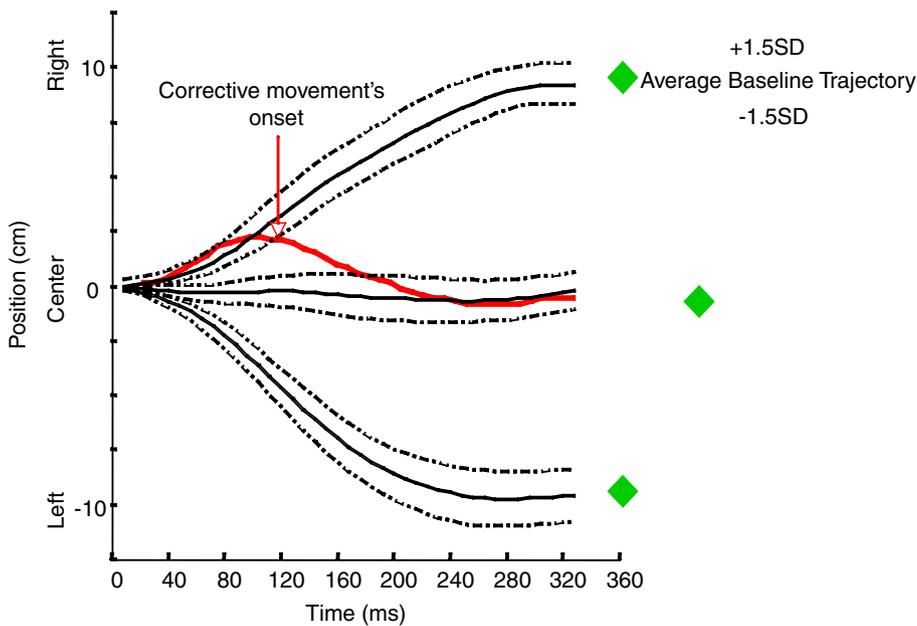


Fig. 3. The identification of the onset of corrective movements. First, the baseline trajectories to each target location in single target trials were averaged for each participant. Then, ± 1.5 standard deviations around each average trajectory were calculated. The point in time when the trajectory crossed this boundary was defined as the onset of *corrective* movement. Movement trajectories were averaged until 40 samplings after movement onset. The target locations were not drawn to scale for the demonstration purpose.

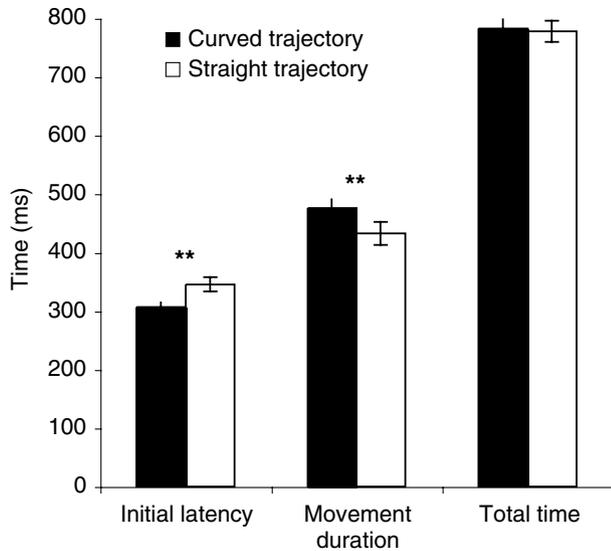


Fig. 4. Comparison between trials showing curved and straight trajectories in terms of mean *initial latency*, mean *movement duration*, and mean *total time*. According to total time, there appears to be no clear overall cost for planning an additional movement. Error bars represent the between-participant standard error (** $p < .006$).

.56 cm (.15) for trials with straight trajectories, and .66 cm (.15) for trials with curved trajectories, $F(1, 7) = .1$, $p = .55$. Thus, reach endpoint errors were not different for trials with curved trajectories compared to those with straight trajectories. Mean horizontal precision was .22 (.11) for trials with straight trajectories, and .23 cm (.11) for trials with curved trajectories, $F(1, 7) = .002$, $p = .93$. Similarly, mean vertical precision was .85(.7) for trials with straight trajectories, and .43(.21) for trials with curved trajectories, $F(1, 7) = .31$, $p = .59$. Thus, reach precision was not also reduced by curved trajectories.

This finding demonstrates that as inefficient as it may seem, trials with highly curved trajectories are no more costly in terms of selection accuracy, landing endpoint error and precision, and time than trials with straight trajectories, demonstrating that new color-oddy targets can be re-selected efficiently.

3.2. Short correction time relative to initial latency

To better understand this efficiency of corrective target selection, we measured the onset of *corrective* movements from the classified curved trajectories. The corrective movement onset was defined as the point in time when the trajectory crossed the one-and-a-half standard deviation limits around the baseline trajectory as depicted in Fig. 3. Then, *correction time* was defined as the intervals between the onset of *initial* movement and the marked *corrective* movement, representing a part of corrective target selection process.

The distribution of correction time (filled bars), pooled from all eight participants is depicted in Fig. 5A. For comparison, the distribution of initial latencies (unfilled bars)

measuring intervals between onsets of stimuli and *initial* movements is plotted together. Compared to initial latencies, which occurred mostly within the 250–350 ms range, correction times are much shorter with a peak at around 100 ms, and the rest of the distribution mostly do not overlap with the initial latency distribution: mean initial latency was 299 ± 53 (SD) ms, whereas correction time was 125 ± 50 (SD) ms. The differences between correction time and initial latency within the same trials are also plotted in Fig. 5B. The mean of this difference distribution (correction time-initial latency) was 171 ± 78 (SD) ms. This trend is also statistically confirmed in all participants, $t(7) = 11.8$, $p < .0001$. This very short correction time suggests that corrective movement planning must begin very early.

In a visual search paradigm, it is not possible to mark when the new corrective target selection process begins. Hence, to further gain insight about how early the target selection process might begin, we adopted a double-step paradigm in the next experiment, which enables us to estimate the onset of such internal events.

3.3. Corrective target selection begins before initial movement onset

Using the double-step paradigm, we estimated how long it takes from the beginning of a new target selection process to the corrective movement onset. To simplify the experiment, a single target is displaced to another location after a certain delay.¹ In this double-step paradigm, the initial movement is elicited by the first target, and the second movement is triggered by the displacing second target (Becker & Jurgens, 1979; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983; Turrell, Bard, Fleury, Teasdale, & Martin, 1998; van Sonderen, Denier van der Gon, & Gielen, 1988).

In this task, an initial target was randomly presented at one of three possible locations. In 65% of the trials, there was no target movement. However, in 35% of the trials, the initial target disappeared and a new target appeared at one of the two other locations after an equally and randomly assigned 150, 200, or 250 ms delay. Since initial movement latencies were typically 250–300 ms [278 ± 47 (SD) ms] as depicted in Fig. 6 (unfilled bars), the target displacement occurred before movement onset. These displacement intervals were chosen based on our pilot study. If the target displacement occurs too early, movements are executed directly

¹ Applying a double-step paradigm to a color-oddy search task may seem more equivalent to the display adopted in our search experiment. However, when a color-oddy target was displaced to one of the distractor locations, which is equivalent to color-swapping among stimuli, the detection of target displacement itself was too difficult (Saiki, 2003). Therefore, to make a target displacement easily noticeable, we used a single target in the same widely spaced configuration of target positions (12.5°) as in our main experiment.

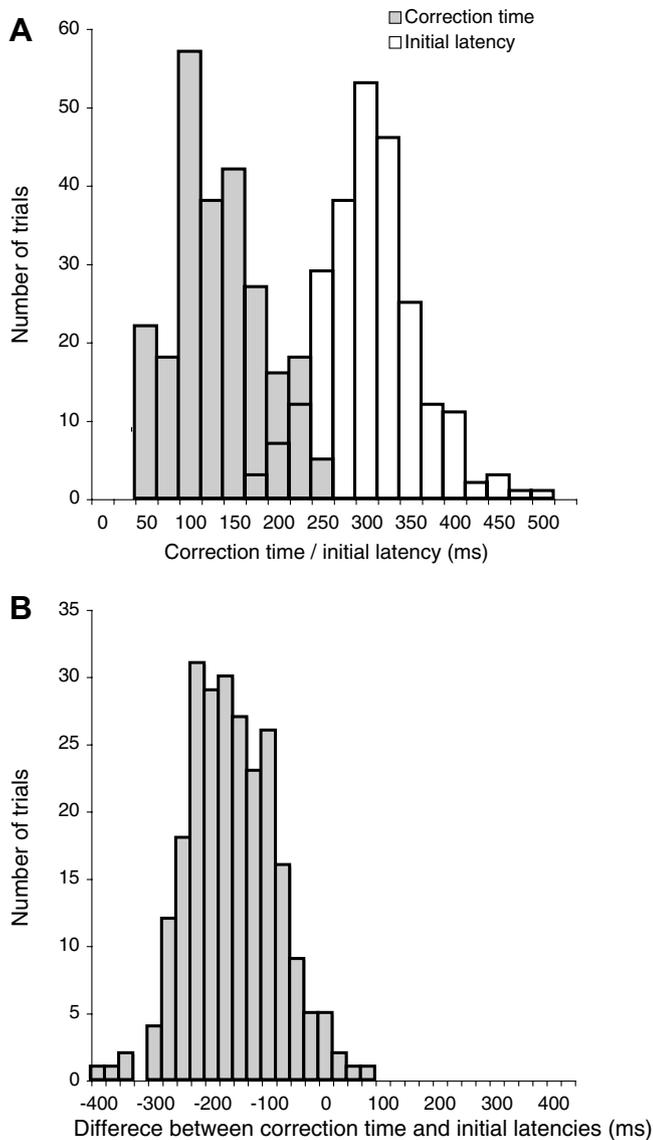


Fig. 5. (A) Correction time (filled bar) and initial latency (unfilled bar) pooled from all eight participants. Most of the correction times are shorter than initial latencies, showing clearly distinctive distributions. (B) The difference between correction times and initial latencies. This graph indicates that the estimated overlap of the concurrent processing is approximately 200 ms.

towards the second target and if too late, it is directed to the initial target so that we could not detect the corrective movement onset (Becker & Jurgens, 1979; van Sondren et al., 1988). Displacement trials were embedded among no-displacement trials to encourage participants to initiate their movements in the same rapid manner on each trial.

In the displaced-target condition, participants typically initiated their reaching movements toward the initial target and corrected them in order to reach the displaced-target as in the visual search task. We examined the time course of two movements separately relative to their corresponding onsets. To obtain time estimates for an entire corrective planning process in this experiment, correction

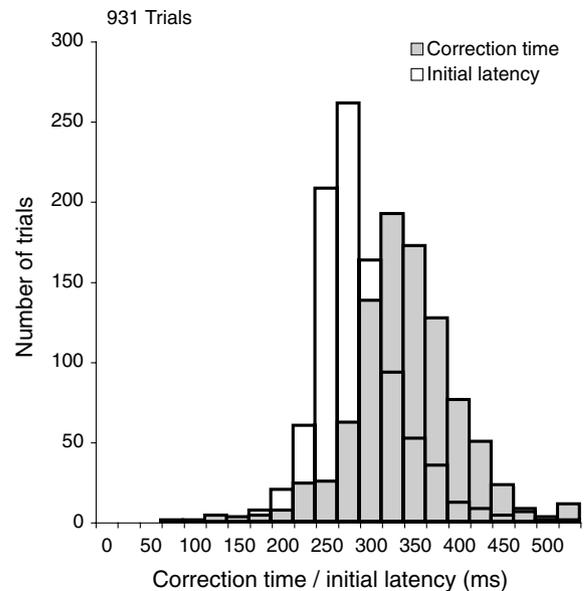


Fig. 6. Comparison between correction time (filled bar), and initial latency (unfilled bar) in the double-step task.

time is calculated from the onset of target displacement (second target), instead of the onset of initial movement.

The distribution of correction time (filled bar), indicating the duration from the target displacement to the onset of trajectory, is plotted in Fig. 6. Mean correction time was 333 ± 64 (SD) ms, suggesting that the onset of corrective movement we detected as an indication of a modified motor plan is approximately 250–350 ms after a new target is presented. For comparison, the distribution of initial latency (unfilled bar) is plotted together, which shows that the time required for selecting each target is approximately equivalent.

Based on this result, we roughly estimate that in our previous visual search task, target re-selection process is likely to begin about 200 ms before initial movement is executed since the onset of corrective movement is 125 ± 50 (SD) ms (Fig. 5A) after the onset of initial movement. In the search task, initial latency is approximately 300 ms, meaning that the planning of the second movement begins well before the first movement is executed.

4. Discussion

Previous studies have provided a wealth of information about how rapidly movement trajectories can be adjusted when the position of a single target is displaced. (Castiello & Jeannerod, 1991; Castiello, Paulignan, & Jeannerod, 1991; Cooke & Diggle, 1984; Elliott & Allard, 1985; Goodale, Pelisson, & Prablanc, 1986; Pisella et al., 2000; Prablanc & Martin, 1992; Soechting & Lacquaniti, 1983). For instance, Goodale et al. (1986) demonstrated that when the target is displaced during the saccadic suppression, participants can change their movement trajectory without adding to more the movement duration.

In the current study, we expanded the notion of rapid movement correction to when a new target selection is required among multiple distractors, which significantly differs from when a single target is displaced. We addressed the question as to how efficiently a target can be re-selected in a visual search task in which multiple competing stimuli are presented and the target feature changes unpredictably across trials. To the best of our knowledge, this study is the first to investigate the efficiency of bottom-up target selection for reach during a reaction-time visual search task.

4.1. Efficient target selection in visual search reflected on fast movement correction

We found that in some trials, we observed highly curved trajectories because initial movements were executed toward a distractor and corrected in mid-flight, indicating that a distractor was initially selected as the target in visual search and a reach movement was executed before the final and correct decision-making was completed. Despite the need to select a new target, no extra time was required to complete these trials.

The detectible onset of corrective movements shortly after the initial movement onset suggests that two competing targets are processed in a timely overlapped manner. Although the real duration required for corrective target selection, which is between the detection of a wrong decision and its correction, is inaccessible through the visual search paradigm, if replacing an initial plan has the same delay as initiating one, then the beginning of the reach new plan has to occur around 150 ms after target onset, approximately equivalent to the difference between correction time and initial latency (Fig. 5B). This difference would correspond to the overlap duration for two concurrent motor plans.² Thus, a seamless and efficient corrective process can occur, made possible by parallel motor plans readied even before the initial erroneous plan is being executed.

We view our results in the context of diffusion models for response decision-making. Separate parallel channels accumulate information for competing responses over time. As soon as the accumulated information for one response reaches the threshold, a motor response can be executed (Palmer, Huk, & Shadlen, 2005; Ratcliff, Cherian, & Segraves, 2003; Smith & Ratcliff, 2004; Stuphorn & Schall, 2002). In our experiments, curved trajectories occur in instances where a distractor channel reaches threshold before a target channel during competition. Thus, a movement toward a distractor is first initiated, and then shortly thereafter, the correct channel reaches threshold and a corrective movement can follow. Such framework thus pro-

vides some explanation as to why misdirected motor movements, hastily initiated, can be corrected with minimal loss in overall efficiency.

The idea of simultaneous processing of competing reach targets has been also supported by recent neurophysiological studies. Cisek and Kalaska (2002, 2005) showed in single cell recordings that when two potential targets were presented for selective reaching, the dorsal premotor areas in monkeys generated two simultaneous signals corresponding to the directions of movement of the two targets. When the post-cue presented 2–3 s later indicated the correct target, the neural activity for the target direction gradually increased while the activity for the distractor was suppressed. Then, after 1–2 s, when the movement onset cue was presented, monkeys correctly executed their reaching movements to the target. This suggests that the premotor areas can represent multiple action plans concurrently, even before a cognitive decision is made about the correct target.

4.2. Concurrent processing for saccades

Examining reach target selection in visual search has the advantage of providing direct comparison with saccades, a paradigm that has been used to study target selection in both humans and monkeys (Basso & Wurtz, 1998; Bichot & Schall, 1999; Bichot & Schall, 2002; McPeck & Keller, 2004; Schall & Hanes, 1993; Thompson, Hanes, Bichot, & Schall, 1996). When a similar color-odddity search paradigm was applied to saccades, McPeck, Skavenski, and Nakayama (2000) observed that human participants sometimes made an initial saccade towards a distractor and very shortly afterwards generated a corrective saccade to the target. Yet, corrective latencies (from 0 to 100 ms) were unusually short compared to typical 200–300 ms saccadic latencies, explained by the concurrent programming of two saccades.

Furthermore, McPeck and Keller (2002) showed in single cell recording that the superior colliculus (SC) is involved in concurrently programmed saccades. During the execution of an initial saccade, activity related to the goal of a quickly-following second saccade can be simultaneously maintained in the SC motor map, appearing to signal the selection or increased salience of the second saccade goal even before the initial saccade has ended. Interestingly, recent studies of the primate and cat have demonstrated that in the SC, a structure traditionally viewed as strictly oculomotor, a class of neurons has recently been identified that are selectively active during visually guided reaches, and involved in the on-line correction of reaching movements (Alstermark, Gorska, Lundberg, & Pettersson, 1990; Courjon, Olivier, & Pélisson, 2004; Pettersson, Lundberg, Alstermark, Isa, & Tantisira, 1997; Stuphorn, Bauswein, & Hoffmann, 2000; Werner, Dannenberg, & Hoffman, 1997). Thus, this raises a question as to whether the SC is also involved in target selection and dynamic trajectory control for reaches.

² We thank an anonymous reviewer for this suggestion. We also acknowledge that in our study, the existence of only three known potential target locations could conceivably represent a special case. To more fully test the generality of our results, a wider range of possible target positions should be examined.

5. Conclusion

In the current study, we showed that hand movements are sometimes initiated before the correct target selection is completed. Furthermore, we showed that the time cost of planning corrective movements is negligible even though a new target is selected for this correction, suggesting that target selection is efficient and competing motor plans overlap temporally. In particular, we demonstrated that movement trajectories provide a real-time readout of perceptual and cognitive internal decision processes during the course of the movement.

Acknowledgments

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