

Reaching for the unknown: Multiple target encoding and real-time decision-making in a rapid reach task

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ARTICLE INFO

Article history:

Received 10 September 2009

Revised 6 April 2010

Accepted 20 April 2010

Keywords:

Decision-making
Multiple target encoding
Parallel competition
Visuomotor control
Movement planning
Reaching

ABSTRACT

Decision-making is central to human cognition. Fundamental to every decision is the ability to internally represent the available choices and their relative costs and benefits. The most basic and frequent decisions we make occur as our motor system chooses and executes only those actions that achieve our current goals. Although these interactions with the environment may appear effortless, this belies what must be incredibly sophisticated visuomotor decision-making processes. In order to measure how visuomotor decisions unfold in real-time, we used a unique reaching paradigm that forced participants to initiate rapid hand movements toward multiple potential targets, with only one being cued *after* reach onset. We show across three experiments that, in cases of target uncertainty, trajectories are spatially sensitive to the probabilistic distribution of targets within the display. Specifically, when presented with two or three target displays, subjects initiate their reaches toward an intermediary or 'averaged' location before correcting their trajectory in-flight to the cued target location. A control experiment suggests that our effect depends on the targets acting as potential reach locations and not as distractors. This study is the first to show that the 'averaging' of target-directed reaching movements depends not only on the spatial position of the targets in the display but also the probability of acting at each target location.

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1. Introduction

We are faced with countless decisions every day, ranging from the somewhat trivial (What shirt should I wear?) to the potentially life-changing (What career should I choose?). The most frequent decisions we make, those made by our motor system, typically occur without conscious deliberation. Consider the scenario of sitting at your desk anticipating an important phone call. You are about to

reach out and pick up your cup of coffee when the phone rings. Rather than having to make the conscious decision to stop reaching for the cup and only then plan a reach towards the phone, you are able to shift seamlessly from the execution of one motor plan to another. To explain this behavior, it has been proposed that multiple potential targets for action are partially encoded in parallel and compete for execution (e.g. Cisek, 2007). In the example just discussed, having partial motor plans both for picking up the phone and for picking up the cup makes the switch from one goal to the other both rapid and efficient.

Some of the most compelling evidence for parallel target encoding comes from neural recordings in macaque monkeys. Areas in premotor cortex (e.g. premotor dorsal) and the midbrain (e.g. superior colliculus) have been shown to simultaneously encode multiple potential targets

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for reach (Cisek & Kalaska, 2005) and eye movements (Basso & Wurtz, 1997, 1998), respectively. Interestingly, these brain regions overlap with, or are reciprocally connected to, areas that represent quantity and probability information (Gold & Shadlen, 2007; Hubbard, Piazza, Pinel, & Dehaene, 2005) – variables that are crucial to comparing and deciding between alternatives. The existence of these interconnected neural circuits has led to the idea that motor decision architecture provides the evolutionary scaffolding for the higher-level decision-making that is central to human cognition (e.g. Cisek, 2007; Gold & Shadlen, 2007). Yet, despite the critical role that motor decision-making clearly plays in our daily lives, and the role it may have played in the evolution of higher-level cognition, the way in which this kind of decision-making unfolds remains poorly understood.

Some insights into the underlying neural mechanisms of human motor decision-making have come from kinematic studies of eye and arm movements made to targets in the presence of non-target visual distractors. Distractors, which often share features with the target but less commonly appear at possible target locations, have been shown to cause deviations of the eyes (Arai, McPeck, & Keller, 2004; Coren & Hoenig, 1972; Findlay & Walker, 1999; McSorley, Haggard, & Walker, 2006, 2009; van der Stigchel, Meeter, & Theeuwes, 2006; Walker, Deubel, Schneider, & Findlay, 1997; Walker, McSorley, & Haggard, 2006) and hand (Chang & Abrams, 2004; Lee, 1999; Sailer, Eggert, Ditterich, & Straube, 2002; Song & Nakayama, 2008b; Tipper, Howard, & Jackson, 1997; Tipper, Lortie, & Baylis, 1992). When a target and distractor appear in close proximity, the endpoints of target-directed eye and arm movements often land between them, an observation which has been termed the ‘global effect’ or ‘spatial averaging’ (Eggert, Sailer, Ditterich, & Straube, 2002; Findlay, 1982; Godijn & Theeuwes, 2002; Ottes, van Gisbergen, & Eggermont, 1984; Sailer et al., 2002; Theeuwes, Kraemer, Hahn, & Irwin, 1998; van der Stigchel et al., 2006). To explain this behavior, it has been posited that closely spaced visual stimuli (targets or distractors) create overlapping hills of activity in the corresponding motor maps of structures involved in movements of the eye (e.g. superior colliculus, McPeck, Han, & Keller, 2003; McPeck & Keller, 2001; Port & Wurtz, 2003; Robinson, 1972; Wurtz, Goldberg, & Robinson, 1980) and arm (e.g. motor cortex, Georgopoulos, Kettner, & Schwartz, 1988; Georgopoulos, Schwartz, & Kettner, 1986), with the final movement vector being determined by the averaging of these signals (Godijn & Theeuwes, 2002; Tipper, Howard, & Houghton, 2000; Tipper et al., 1997; Tipper, Howard, & Paul, 2001). Indeed, where the spatial averaging of eye movements have been observed, activity in the superior colliculus appears greatest at an intermediary location between the two targets (Glimcher & Sparks, 1993; van Opstal, van Gisbergen, & Smit, 1990). Under this view, both targets and distractors are therefore thought to be initially represented as potential targets by the visuomotor system (McPeck & Keller, 2004). It has been postulated that top-down inhibitory signals can dampen the activity associated with a distractor (McSorley & McCloy, 2009; Tipper et al., 1997), with the level of inhibition being a function

of time: with insufficient time to completely suppress distractor activity, movements will be partially deviated towards a distractor (e.g. Eggert et al., 2002; Lee, 1999); when inhibition has had long enough to suppress the distractor activation below baseline, movements will actually deviate away from the distractor (Tipper et al., 1997; van der Stigchel et al., 2006 for review; Walker et al., 2006). Given that the deviations induced by distractors seem temporally dependant, it follows that distractor effects should also be contingent on prior expectations as well as the latency of the eye- or arm-movement. Indeed, spatial averaging is much less likely to be observed when subjects can anticipate the location of a distractor (van der Stigchel & Theeuwes, 2006; Walker et al., 2006) or have increasing time to prepare the target-directed action (e.g. Cardoso-Leite & Gorea, 2009; Eggert et al., 2002; Favilla, 1997, 2002; Ghez et al., 1997; Lee, 1999; Theeuwes et al., 1998). Although distractor interference results provide a window into the target selection process, rarely are distractors identical to the targets – differing along a critical dimension such as color or location, and never intended to be targets for action. In this way, distractors only compete with targets indirectly.

In addition to what has been learned from studies of distractor-related tasks, other insights into the neural processes of decision-making have come from observing how sensory information presented at different stages of motor planning can affect the execution of reach movements. For example, it has been shown that reaches are initiated more quickly to precued target locations (Bock & Arnold, 1992; Bock & Eversheim, 2000; Goodman & Kelso, 1980; Pellizzer & Hedges, 2003, 2004; Rosenbaum, 1980) and that the degree to which the precue influences the path of the trajectory appears to be a function of the time between the precue and movement onset (Favilla, 1997, 2002; Ghez et al., 1997). Also, in agreement with the distractor findings, visual stimuli presented concurrently with the target appear to be automatically encoded regardless of whether the information is to be used (e.g. Trommershauser, Maloney, & Landy, 2008) or ignored (Chang & Abrams, 2004; Song & Nakayama, 2006; Tipper et al., 1992). Finally, it has been shown that task-related information presented during the reach (Cressman, Franks, Enns, & Chua, 2007; Schmidt, 2002) can be incorporated into the movement in-flight, even when that information is not consciously perceived.

From this evidence it has been eloquently argued that rapid reaching tasks, and the subsequent analysis of trajectories, can provide a unique window into underlying cognitive processes that ‘leak’ into movement execution (Song & Nakayama, 2006, 2008a, 2009). With this in mind, many of the effects on reach behaviors described in the above examples might *indirectly* measure the parallel planning of multiple actions. For example, the time varying effects distractors have on movements is an indirect reflection of what is thought to be a decaying unselected motor plan. In the current experiment, rather than assuming that distractor information leaks into reaching behavior, we forced people to initiate a rapid reach toward multiple potential targets *before* one of the targets was cued for action. Moreover, rather than differentiating a target from a distractor

in any way, the paradigm was designed so that all visual items were identical prior to movement onset and competed equally as potential targets. In this way, we intentionally merged the final stages of planning an action, when all display items needed to be considered as potential targets, with the on-line control of a rapid reaching movement. The analysis of our reach trajectories therefore directly measures how (and when) the decision to act on the cued target is made.

In three experiments, we measured the moment-to-moment kinematics of motor decisions. In the first experiment, we presented single target or two target displays. We show that people aim directly for the single targets but toward the midpoint of the two target displays, consistent with the previously reported global effect. This suggests that participants produce an averaged trajectory rather than make an arbitrary guess toward one of the two equally probable target positions. In the second experiment, we presented distractors simultaneously with an already selected target and replicated the single target results of Experiment 1, suggesting the spatial averaging we observed depended on the targets being viewed as potential goal locations, not as irrelevant distractors. Lastly, given the consistency with which our participants produced averaged trajectories, in a third experiment we tested the limits of this sensitivity by varying target positions and introducing displays with three targets. This allowed us to directly manipulate two critical aspects of the display: First, **by manipulating the distance between two potential targets, we were able to shift the midpoint**

between them and thus manipulate the spatial distribution of targets within a display. Second, by putting two targets on one side of space, and one target on the other we were able **to manipulate the probabilistic distribution of the targets within the display.** Remarkably, we found that initial trajectories still reflected an averaging behavior, and for the first time show that participants were also biased toward the side of space containing the greater number of potential targets. With our paradigm we show that the initial trajectory is a measure of the motor plan toward multiple potential targets and the subsequent in-flight correction represents the timing and execution of the on-line decision to act on the cued target.

2. Experiments 1 and 2

2.1. Methods

We recorded rapid reach movements (OPTOTRAK, 150 Hz) from 15 (Experiment 1) and 17 (Experiment 2) right-handed subjects as they reached from a start button to a touch screen (40 cm away). Trials began with participants holding down the start button and fixating a cross centered on screen (1000–2000 ms). A beep signaled when fixation was replaced by a target display, consisting of one or two outlined-targets (black, on a white background), and also provided the cue for subjects to initiate a reach (within 325 ms). Upon button-release, one of the target(s) in the display was cued (filled-in black) and subjects had to correct their trajectory in-flight to that location (within

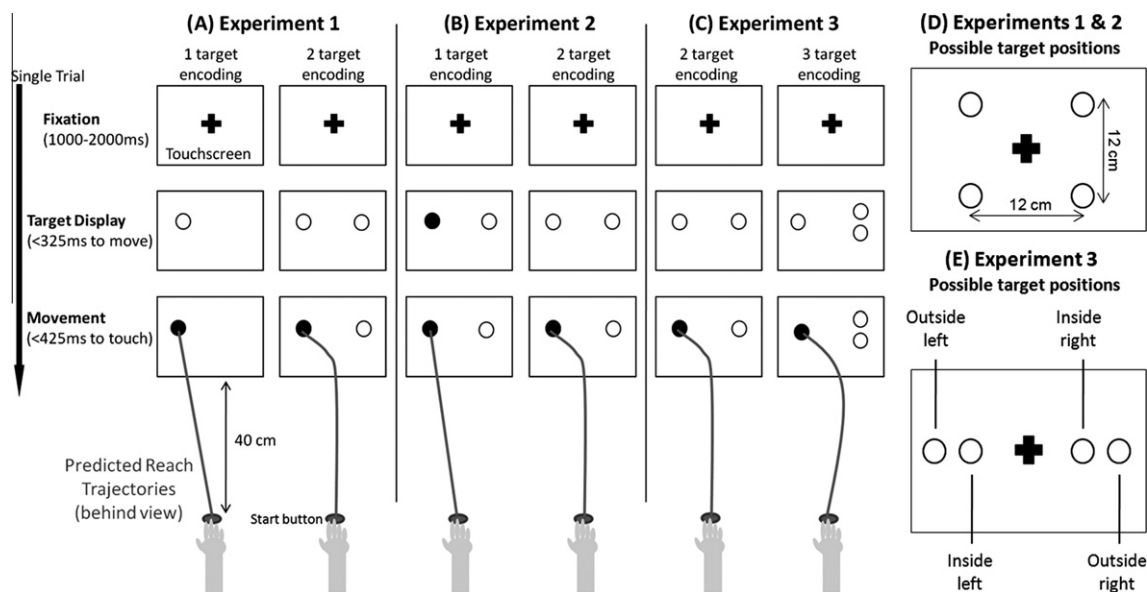


Fig. 1. Experimental timings and example displays for all three experiments. Trials began with the subject fixating a cross for a variable time interval (1000–2000 ms). This was followed by a target display containing one, two or three possible targets which also provided the cue for subjects to initiate a reach to touch a target that would be filled-in at movement onset (note one exception – the target could also be filled-in concurrently with display presentation for early trials in Experiment 2; left panel in B). Importantly, each unfilled target in the display always had an equal probability of filling-in. Upon target display presentation subjects had 325 ms to lift their finger off the start button, and then an additional 425 ms to reach and touch the cued target. A: Experiment 1, single and two target trials. B: Experiment 2, single (early target cue) and two (late target cue) target trials. C: Experiment 3, two and three target trials (example single target trials not shown). Below A–C are hypothesized reach trajectories (gray traces). D: possible target positions in Experiment 2. E: possible target positions in Experiment 3. On three target trials, two of the targets would appear vertically stacked at one of the positions, with the third target appearing on the opposite side of space. Note in D & E fixation is shown for reference and did not appear on the screen with the targets.

425 ms) (see Fig. 1). **Importantly, all targets in the display had an equal probability of filling-in.** To ensure rapid and accurate movements subjects received feedback on the screen following each trial. There were four possible types of errors which caused the following text to be displayed at the center of the screen: *Too Early* (if the start button was

released before 100 ms had elapsed), *Time Out* (if the start button was not released within 325 ms), *Too Slow* (if the screen was not touched within 425 ms of button-release) or *Miss* (if subjects did not touch within a 6 cm × 6 cm box centered on the target). *Good* was displayed on trials without errors.

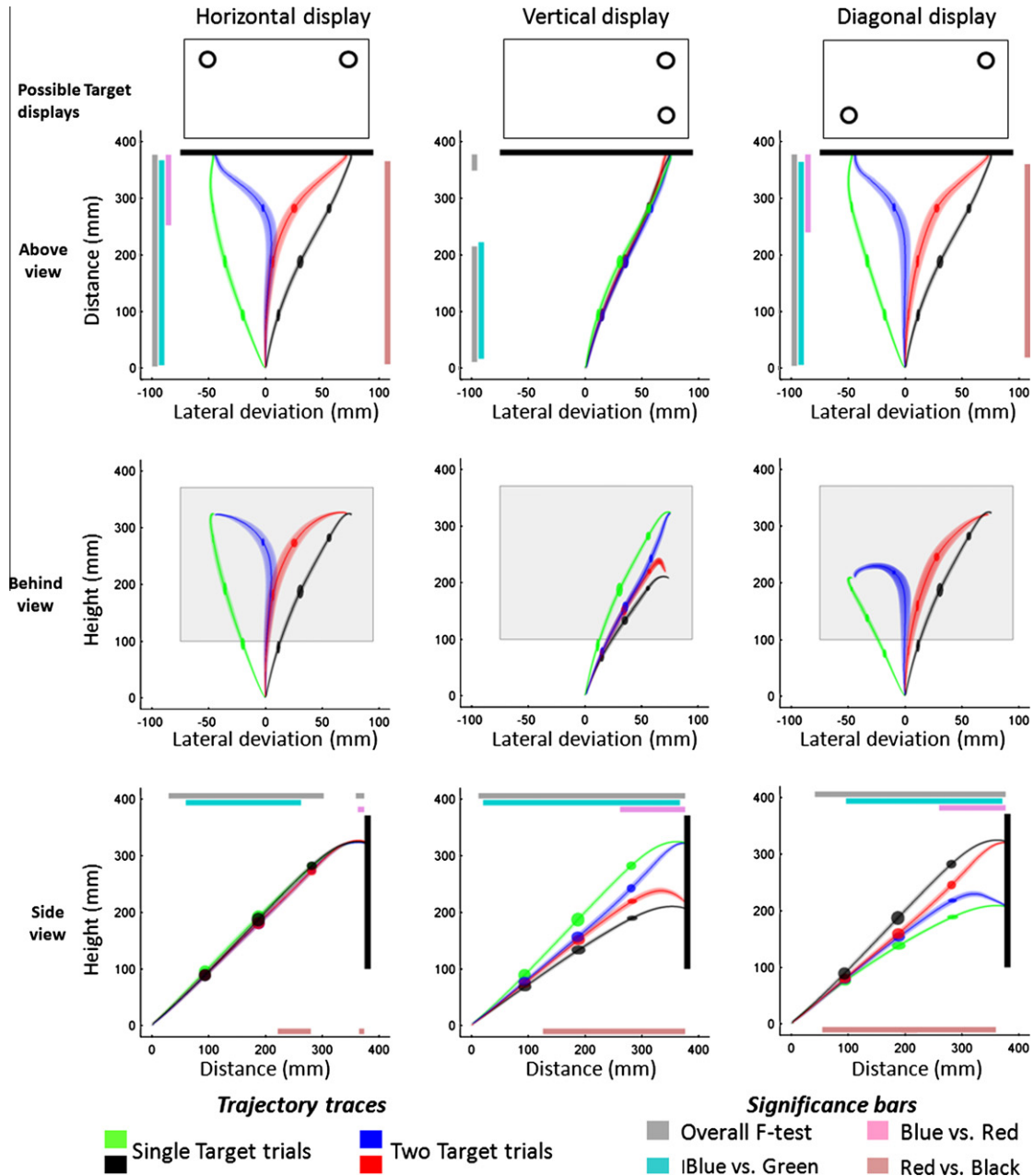


Fig. 2. Averaged three-dimensional reach trajectories from Experiment 1 shown from: above (top-row, x-axis is twice scale), behind (middle-row, x-axis is twice scale) and side (bottom-row). Participants made reaches from a start button (0, 0, 0) to a touch screen located 40 cm away (denoted by thick black line and grey rectangle). Target displays contained either one (single target trials, black- and green-traces) or two (two target trials, blue- and red-traces) hollow circles arranged horizontally (left-column), vertically (middle-column) or diagonally (right-column). Tubes around trajectory traces represent average standard error across 14 participants with darkened spheres at 25%, 50% and 75% of reach distance proportional to the velocity in each dimension. Significance bars located in the above and side view plots give a measure of where there were statistical differences (Greenhouse–Geisser corrected repeated-measures ANOVA, $p < 0.05$) between trajectories in the lateral and height dimensions, respectively. Note that target displays (at top) are not drawn to scale.

One and two target displays were selected from four possible target locations, arranged in a 12 cm square centered on the fixation (see Fig. 1 and Supplemental Table 1). In single target trials for Experiment 1, subjects knew in advance the final location of the target to be selected. In two target trials, targets could be aligned horizontally (top or bottom), vertically (left or right) or diagonally and therefore, prior to movement onset, subjects needed to prepare for either target to be selected. The design, stimuli and timing of Experiment 2 were identical to Experiment 1 with the exception that (1) Two targets always appeared on the screen (horizontal top or bottom only) and (2) the target could be filled-in at movement onset ('Late' trials) or at the time of the target display presentation ('Early' trials) (see Fig. 1). Participants completed 320 (Experiment 1: 2 repetitions of 16 conditions for 10 blocks) or 80 (Experiment 2: 1 repetition of 8 conditions for 10 blocks) correct trials.

2.2. Results and discussion

Participants were excluded from analysis if they made errors on more than 50% of the two target trials (1 participant – Experiment 1) or 'Late' trials (3 participants – Experiment 2) [for complete error analysis see Supplemental material]. Only Good trials were analyzed from the remaining participants ($n = 14$ for both experiments). The striking effect of multiple potential targets is most clearly seen in the reach trajectories (Figs. 2 and 3). In Experiment 1, on trials when only a single target was presented (Fig. 2, black- and green-traces), reaches were made straight towards it. Importantly, however, reaches to two target displays (red- and blue-traces) were initially aimed at the midpoint of the two targets, before the trajectory was corrected to the cued position in-flight (see also Supplemental Fig. S1). This was confirmed statistically using two functional-ANOVAs (Ramsay & Silverman, 2005, see Supplemental material) within each display comparing the lateral (x) and vertical (z) deviation at different reach-distances (y) across the single and two target trajectories. This statistically sensitive technique, which extends a traditional univariate ANOVA to all points in a curve, allows a quantification of not only if, but also where, two trajectories differ. In all cases, functional-ANOVAs along the dimension of separation (e.g. x for horizontal displays, values reported below correspond to the Horizontal display shown in Fig. 2, but all displays show the same pattern) were statistically significant (where Greenhouse–Geisser corrected $p < 0.05$) from very early ($<1\% \leq 0.5$ cm of y -movement, see gray significance bars in Fig. 2) until the end of the reach ($100\% = 40$ cm of y -movement). Follow-up functional comparisons (where Bonferroni corrected $p < 0.05$) confirmed what is visually apparent; i.e., the significant functional-ANOVA was driven by three different initial reach trajectories: one toward each of the single targets, and a third toward the middle of the display when two potential targets were presented. Critically, the reaches toward two target displays did not statistically differ until much later in the reach ($65\% = 25$ cm of y -movement, see pink significance bars in Fig. 2) but were separated from the single target trials very early in the

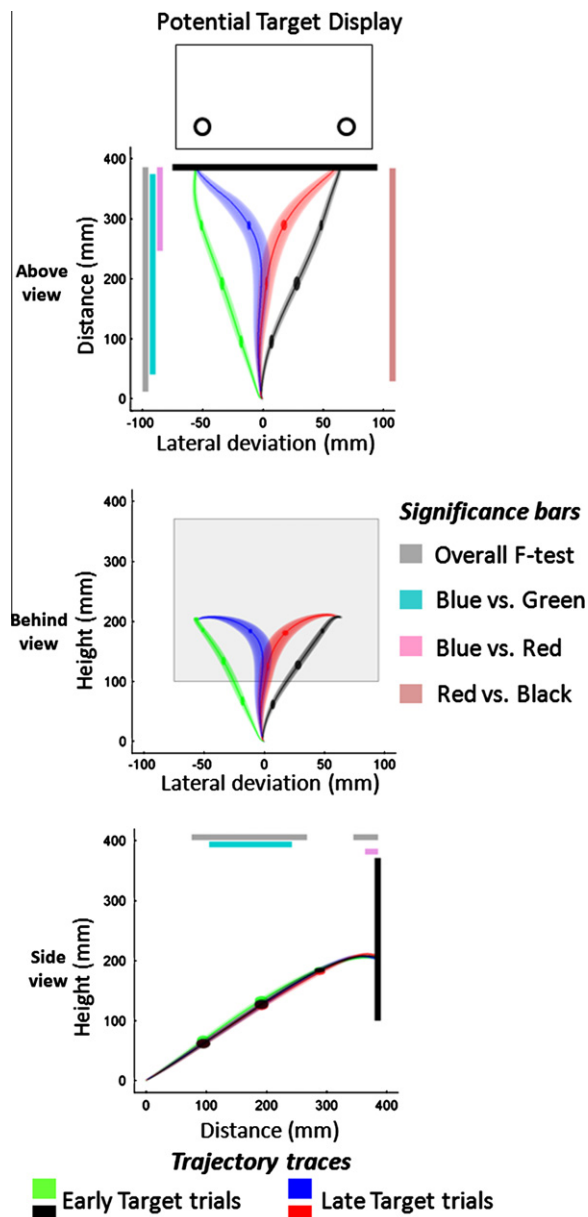


Fig. 3. Averaged three-dimensional reach trajectories from Experiment 2 for 14 subjects shown in the same format as Fig. 2. Green- and black-traces now represent trajectories on 'Early' trials and red- and blue-traces now represent trajectories on 'Late' trials.

reach ($<1\% \leq 0.5$ cm of y -movement, see light-blue and dark-red significance bars, Fig. 2).

There are two possible, though not exclusive, explanations of the spatial averaging observed in Experiment 1: **the midpoint trajectories may (1) reflect that both visual items are being equally encoded as potential targets or (2) be the result of an under-inhibited visual distractor (uncued target) interfering with the reach** (similar to the cognitive 'leaking' described by Song & Nakayama, 2009). To test between these alternatives, Experiment 2 always presented displays containing two targets but manipulated

the timing of target cuing, with the final target being cued either early (at the time of display presentation) or late (at movement onset) into movement planning (see Fig. 1). In this way, 'Early' trials were equivalent to single target trials in that the final target was cued before reach initiation, and yet they controlled for the potential distracting effects of the non-selected target.

Trajectory results from Experiment 2 are shown in Fig. 3 and suggest that the uncued second target that was present on 'Early' trials did not function as a distractor or as a potential target. That is, trajectories to targets that were cued early were straight and did not deviate towards the second visual item. Experiment 2 therefore replicates the findings in Experiment 1 with 'Early' trials behaving like single target trials and 'Late' trials replicating the midpoint effect seen on two target trials (see Fig. 3, note the pattern of significance denoted by the significance bars is identical to Experiment 1).

To confirm that participants were not treating the uncued target as a distractor, we conducted an analysis of trajectory deviation as a function of reaction time (response latency) for both Experiments 1 and 2. It has been well established in the eye-movement literature that short latency responses (where inhibition has not had time to develop) are drawn towards a visual distractor more than long latency responses (where inhibition has developed, e.g. Eggert et al., 2002; Godijn & Theeuwes, 2002; McSorley et al., 2006; van der Stigchel et al., 2006 for review). To test for this effect in our data we analyzed all trials with two initially uncued targets that were separated along the horizontal (x) dimension (Horizontal and Diagonal displays for Experiment 1, and 'Late' trials for Experiment 2). Since the hand starts at the lateral midpoint between the two targets for these displays we were able to quantify the deviation toward the 'distractor' (i.e. uncued target location) as the maximum lateral (x) deviation toward the side of space opposite the cued target. Each participant's latency distribution on these trials was grouped into bins of 20% (quintiles) and the deviation toward the distractor averaged for each bin. A Greenhouse–Geisser corrected repeated-measures ANOVA of maximum deviation toward the distractor across the five quintiles was not significant for either Experiment 1 (0–20%: 15.01 mm, 20–40%: 18.02 mm, 40–60%: 16.77 mm, 60–80%: 16.32 mm and 80–100%: 16.13 mm [$F(2.3, 30.3) = 1.98$, $p = 0.15$]) or Experiment 2 (0–20%: 14.95 mm, 20–40%: 17.01 mm, 40–60%: 16.17 mm, 60–80%: 15.45 mm and 80–100%: 19.60 mm [$F(3.0, 39.5) = 1.20$, $p = 0.32$]). Together with the trajectory evidence, we are therefore confident that the effects we report cannot be explained by claiming the uncued target was functioning as an under-inhibited distractor.

For additional analysis of reaction time and other kinematic measures from all three experiments see Supplemental material and Supplemental Table 1.

3. Experiment 3

We wanted to test whether the remarkably sensitive averaging behavior observed in the first two experiments would extend to displays with different spatial and proba-

bilistic distributions of potential targets. To this end, Experiment 3 manipulated both the location of the midpoint between two targets (display width) and the number of targets on the screen. We hypothesized that initial reach trajectories would reflect target probabilities inherent in the display – being shifted toward a new midpoint position and biased to the side of space with more targets.

3.1. Methods

In Experiment 3 (22 right-handed participants), the stimuli, apparatus and timing were identical to Experiments 1 and 2 with the exception that we changed both the number and location of potential targets. Targets could appear at four different horizontal positions at the same height as fixation – outside or inside left (12 and 6 cm to the left of midline, respectively) and outside or inside right (12 and 6 cm to the right of midline) – in displays of one, two or three targets (see Figs. 1 and 4 and Supplemental Table 1). In two and three target displays there was always at least one target on both the left and right. On three target trials, the third target appeared coupled (vertically stacked, same horizontal position) with another target. Throughout the experiment targets were equally distributed across all possible positions. As such, despite subjects not knowing the final target location prior to movement onset, the three target display biased the probability (2/3) of a target being selected at a particular location. Participants completed 420 total trials (28 conditions distributed randomly across 10 blocks).

3.2. Results

Four participants were removed from analysis due to poor performance (more than 50% errors on the two and three target trials). To improve our estimate of participants' reach behavior we analyzed both *Good* trials and *Too Slow* trials, provided that the movement time on the *Too Slow* trial fell within 1 standard deviation of that participant's mean movement time. We replicated the behavior observed in Experiment 1 with straight reaches to single targets (black- and green-traces, Fig. 4) and an averaging behavior on trials with two targets (red- and blue-traces, Fig. 4A). By using two target stimuli that varied in display width, we were able to manipulate the position of their midpoint. Initial reach trajectories followed these horizontal shifts in midpoint (Fig. 4A) with reaches toward displays with a potential target in the outside position (red-traces) being pulled in that direction relative to reaches made with targets in an inside position (blue-traces). A planned functional comparison confirmed this midpoint shift (pink significance bars in Fig. 4A show where the blue- and red-traces differ at $p < 0.05$). Importantly, Experiment 3 also investigated the reach response to three potential targets unequally distributed across space (Fig. 4B). Consistent with our predictions, the initial reach trajectories were reliably biased toward the side of space containing more targets (red- and blue-traces, Fig. 4B). Planned functional comparisons (where $p < 0.05$) revealed two types of initial trajectories: those made toward two target-left displays (blue-traces) and those

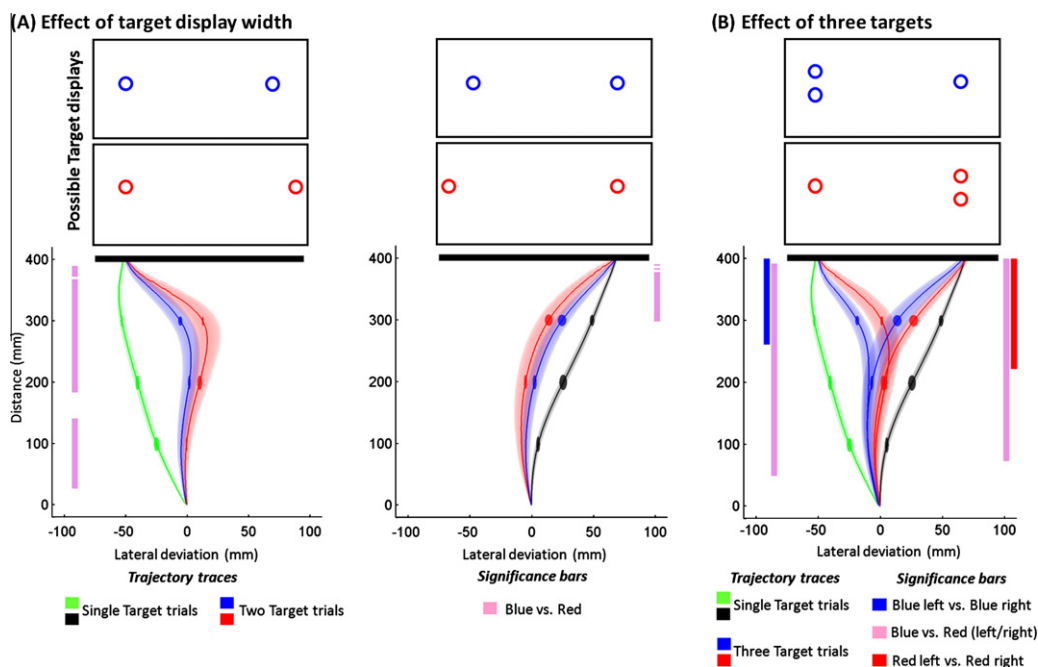


Fig. 4. Average reach trajectories from 18 participants in Experiment 3 (shown from above, with error, timing and single target trials as in Fig. 2) when manipulating (A) target display width and (B) the number of targets. A: reaches to inside-left (left panel) or inside-right (right panel) endpoint when a second target, on the opposite side, was inside (blue-traces) or outside (red-traces). B: Three target trials. Blue-traces: trajectories to a two target left, one target right display; red-traces: trajectories to a two target right, one target left display. Significance bars provide a measure of statistical differences between trajectories in the lateral dimension. Note that target displays (at top) are not drawn to scale.

made toward two target-right displays (red-traces). These two initial trajectories persisted quite far into the reach before separating (blue significance bars indicate where the two target-left displays separated: $65\% = 26$ cm of y-movement, red significance bars indicate where the two target-right displays separated: $55\% = 22$ cm of y-movement) and, rather remarkably, these two headings differed from each other quite early in the movement (pink significance bars, Fig. 4B; for movements ending left: $12\% = 5$ cm of y-movement, for movements ending right: $18\% = 7$ cm of y-movement). Notably, these target-number related biases resulted in subtle deviations away from the simple midpoint, independent of display width, yet remained significantly different from trajectories on the single target trials.

4. General discussion

Our results across the three experiments show that when subjects are simultaneously presented with multiple competing targets and forced to act quickly, they initiate trajectories that reflect a probabilistically weighted average that takes into account both the location and the number of potential targets, before the movement is corrected in-flight to the cued target location. **The initial trajectory and the subsequent motor decision made between targets provide a unique glimpse into how visuomotor decision-making evolves in real-time.**

Fundamental to the formation of any decision is a neural representation of the possible choices to be made – whether those choices are being made in the context of a

low-level perceptuo-motor or high-level cognitive task. In fact, electrophysiological recordings in monkeys show that neurons in the motor and visual systems appear to simultaneously encode multiple potential target locations for upcoming limb and eye movements (Basso & Wurtz, 1997, 1998; Cisek & Kalaska, 2005). These findings provide compelling evidence that the brain specifies multiple possible motor actions before selecting what action it wants to perform – presumably a product of the evolutionary demands for rapid action-selection (Cisek, 2007).

In humans, however, where the use of invasive neural techniques is necessarily limited, investigating the moment-to-moment dynamics of decision-making is more challenging. This is particularly true in the paradigms used in most laboratory situations where the actions to be performed are selected *before* the movements are initiated. Recent studies that have examined rapid reaching movements have shown that cognitive states held prior to the movement can ‘leak’ into the reach (for review see Song & Nakayama, 2009), but they rarely use paradigms designed to test the effect of directly-competing, equally-weighted motor plans. More often, these tasks rely on the need for participants to inhibit what is thought to be an automatically generated visuomotor response to a distractor. These distractors differ from the target along a critical dimension (e.g. color, Schmidt, 2002; Song & Nakayama, 2008b; Tipper et al., 1992) and within a single trial, are never the targets of action. In these tasks, there is likely a context of inhibition, where participants *know* they will have to ignore some of the incoming visual stimuli. It

is unclear how this context influences the bottom-up visual processing of stimuli features and how this ultimately influences the competition between targets and distractors (e.g. in a task with red targets and yellow distractors (as in Tipper et al., 1992), there might be biased processing for the color red). We provide one possible solution to this problem by presenting subjects with a display of multiple equiprobable potential targets but withhold the critical information (cueing one of the targets) for making the decision until movement onset. In this way, during planning we force the visuomotor system to equally represent all the visually identical items as possible targets for the reach. This may explain why even when we embed typical distractor trials in the context of direct target competition (experiment 2, 'Early' trials), we see no evidence for distractor interference in the movement trajectories. While it is possible that in these trials an inhibitory process has developed during the reaction time, the fact that we see no latency dependant interference effects argues against this interpretation.

Our rapid-reach paradigm and trajectory analyses can therefore provide an important and sensitive tool for behavioral researchers wanting to compare the initial encoding and subsequent decision to act on competing stimuli. Whereas previous work that has been restricted to discrete responses (e.g. keypresses) measures only the outcome of a decision, the current paradigm, in which the final target (selected from equally probable potential targets) is cued in-flight, yields a continuous measure of the entire decision-making process. Recently, other researchers have also successfully used continuous reaching as a measure of underlying cognitive processing (e.g. Cressman et al., 2007; McKinstry, Dale, & Spivey, 2008; Schmidt, 2002; Song & Nakayama, 2006; Spivey, Grosjean, & Knoblich, 2005; Trommershauser et al., 2008). This work picks up on a rich history of experiments which examine the automatic online correction of movements to targets whose final position is specified during the movement (e.g. Goodale, Pelisson, & Prablanc, 1986; Pisella et al., 2000).

Our findings provide evidence that is highly consistent with the suggestions that the visuomotor system plans multiple motor programs in parallel (e.g. Cisek, 2007) and the subsequent motor act is an average between them. The convergence of results demonstrating averaging behaviors independent of the acting effector (hand or eye) suggests that the simultaneous encoding of potential movements is a decision-making strategy employed throughout the visuomotor system. Given the novel demonstration that the initial reach trajectory is modulated by the probability of target distribution, an interesting direction for future studies will be to ask how many potential targets can be rapidly and simultaneously encoded and compare this limit to the capacities of working-memory and attention, as well as the limits of the subitizing range.

Acknowledgements

This work was supported by operating grants from the Natural Sciences and Engineering Research Council to Jody

Culham (Grant# 249877-2006 RGPIN) and Melvyn Goodale (Grant# 6313-2007 RGPIN).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cognition.2010.04.008.

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