


One to Four, and Nothing More: Nonconscious Parallel Individuation of Objects During Action Planning

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Abstract

Much of the current understanding about the capacity limits on the number of objects that can be simultaneously processed comes from studies of visual short-term memory, attention, and numerical cognition. Consistent reports suggest that, despite large variability in the perceptual tasks administered (e.g., object tracking, counting), a limit of three to four visual items can be independently processed in parallel. In the research reported here, we asked whether this limit also extends to the domain of action planning. Using a unique rapid visuomotor task and a novel analysis of reach trajectories, we demonstrated an upper limit to the number of targets that can be simultaneously encoded for action, a capacity limit that also turns out to be no more than three to four. Our findings suggest that conscious perceptual processing and nonconscious movement planning are constrained by a common underlying mechanism limited by the number of items that can be simultaneously represented.

Keywords

motor planning, reaching, subitizing, enumeration, attention, capacity, number, perception, action

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People live in a dynamic and complex world in which they are constantly faced with an overwhelming influx of sensory information that is continuously filtered by perceptual and action-planning processes. These processes extract and internally represent multiple relevant visual items from the surrounding world. In perceptual tasks, it has been reliably demonstrated across different subdisciplines (e.g., visual attention, numerical cognition) that the brain can process up to three or four visual objects in parallel before having to rely on additional mechanisms, such as counting or estimation (Dehaene, 1997; Kaufman, Lord, Reese, & Volkmann, 1949; Luck & Vogel, 1997; Pylyshyn & Storm, 1988; Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Trick & Pylyshyn, 1994). These limits also appear to extend to tactile perception (Riggs et al., 2006; although see Gallace, Tan, & Spence, 2008), suggesting that there exists a general perceptual mechanism specialized for quantifying small sets of objects. Despite the consistent observation of this approximately-four-item bottleneck and its role in several prominent theories of vision and attention (Cowan, 2001; Pylyshyn, 1998), to date, this capacity limit has been observed only in purely perceptual tasks, that is, tasks in which participants are required to either count or recall

the number of items presented to them, and performance is measured according to the percentage of correct responses and reaction times (e.g., Franconeri, Jonathan, & Scimeca, 2010; Kaufman et al., 1949). This raises the question as to whether this capacity limit reflects a capacity of higher-level conscious processing (i.e., being able to report the quantity of items) or a more basic nonconscious capacity tied to automatic parallel-processing strategies in the brain.

To investigate this question, we examined whether the capacity limit in rapid visuomotor planning, an inherently nonconscious process (Goodale & Milner, 2004), would show a similar bottleneck to that observed in purely perceptual tasks. We previously developed a rapid-movement paradigm that provides a continuous measure of visuomotor processing (Chapman et al., 2010) and that allows a quantification of the number of potential visual targets that can be simultaneously maintained in parallel. In this manual aiming task, subjects

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were forced to initiate speeded arm movements toward multiple potential targets before one of the targets was cued for action. Using this task, we showed that when there was an equal number of targets on each side of a display, participants aimed their initial reach trajectories toward a midpoint between potential targets (Chapman et al., 2010). This finding is highly consistent with the results of neural and modeling studies showing that multiple potential targets for action are simultaneously encoded in parallel before execution (Cisek & Kalaska, 2010). Moreover, we showed that initial reach trajectories were also biased toward the side of the display containing more potential targets.

In the study reported here, we predicted that if the capacity limit of three to four items traditionally observed in explicit perceptual tasks reflects a more basic nonconscious enumeration capacity in the brain, initial reach trajectories would be increasingly biased toward the side of a display containing more potential targets. However, the presentation of more than three or four potential targets—despite altering the probability of each target location being cued—would have no further effect on the spatial bias of reach trajectories.

Main Experiment

Method

We recorded rapid reach movements (sampling rate of 150 Hz) from 22 right-handed subjects as they reached from a start button to a touch screen (40 cm distance). Trials began with participants holding down the start button with their right index finger and fixating on a cross centered on screen for 1,000 ms to 2,000 ms. A beep signaled the appearance of a target display, which consisted of multiple potential targets (unfilled circles, 2 cm diameter each) on a white background. Varying numbers of circles were arranged on the right and left sides of the display. The beep also provided the cue for subjects to release the start button and reach toward the target display (within 325 ms). After subjects released the button, one of the targets in the display filled in black to cue subjects to correct their trajectory in flight to that location. Subjects had to touch the cued circle within 425 ms (see Fig. 1; see also Video S1 in the Supplemental Material available online). It is critical to note that all targets in the display were equally likely to fill in. As such, subjects needed to take into consideration all potential targets when planning their movements.

Our previous work (Chapman et al., 2010) showed that when there are an equal number of targets on each side of a display, initial reach trajectories are aimed toward a spatially averaged location between potential targets. In other words, subjects initiated informed reaches on the basis of the probability of each target being cued and did not just arbitrarily select one target out of many to reach toward. In the study reported here, we capitalized on this finding in order to provide a sensitive behavioral measure of the number of visual targets that can be simultaneously considered for action. To

detect this limit, we parametrically varied the number of potential targets presented on each side of the display. One side always contained two potential targets; the other side contained between zero and eight potential targets (i.e., the constant:variable ratio ranged between 2:0 and 2:8). The constant side varied randomly between the left and right of the display on each trial, and all individual target locations on each side were randomly selected from nine possible target positions. The centers of the left and right target clusters were separated by 18 cm.

To ensure rapid and accurate movements, we provided performance feedback on the touch screen following each trial. There were four possible types of errors. “Too Early” appeared when the start button was released before 100 ms had elapsed; this aborted the trial. “Time Out” appeared if the start button was not released within 325 ms; this also aborted the trial. “Too Slow” appeared if the screen was not touched within 425 ms of button release, and “Miss” appeared if subjects did not touch the screen within a 6-cm \times 6-cm area centered on the cued target. “Good” was displayed on trials without errors. Subjects performed an initial training session of at least 110 trials followed by 550 test trials (separated across 10 blocks). Additional information about the participants, stimuli, and procedures can be found in Methods and Analyses in the Supplemental Material.

Results

We created a statistically sensitive rendering of the entire reach trajectory that allowed us to examine not only where but also to what extent trajectories from separate trials differed from one another (see Methods and Analyses in the Supplemental Material for a detailed explanation of this and other analyses conducted on data from the main experiment). As the ratio of potential targets increased from 2:1 through 2:4, initial movements were incrementally biased toward the variable side of the display (see Fig. 2, first and third rows). It is important to note, however, that for displays containing more than four potential targets on one side (i.e., 2:5 through 2:8 displays), no additional shifts in initial movement toward the higher number of targets were observed (Fig. 2, second and fourth rows).

This effect was confirmed with a more traditional analysis comparing the lateral position of each subject’s reach trajectories at 60% of the reach distance in a repeated measures ANOVA. Our previous findings (Chapman et al., 2010) showed that arm trajectories at 60% of movement distance have generally reached their maximal lateral deviation but subjects have not yet corrected their in-flight heading toward the location of the cued target. As such, deviations at 60% of reach distance provide a good measure of initial target encoding (and the initially specified motor plan) independent of on-line corrections that manifest later in the movement.

To investigate the ANOVA findings further and to determine whether the significant effects were due to trajectory

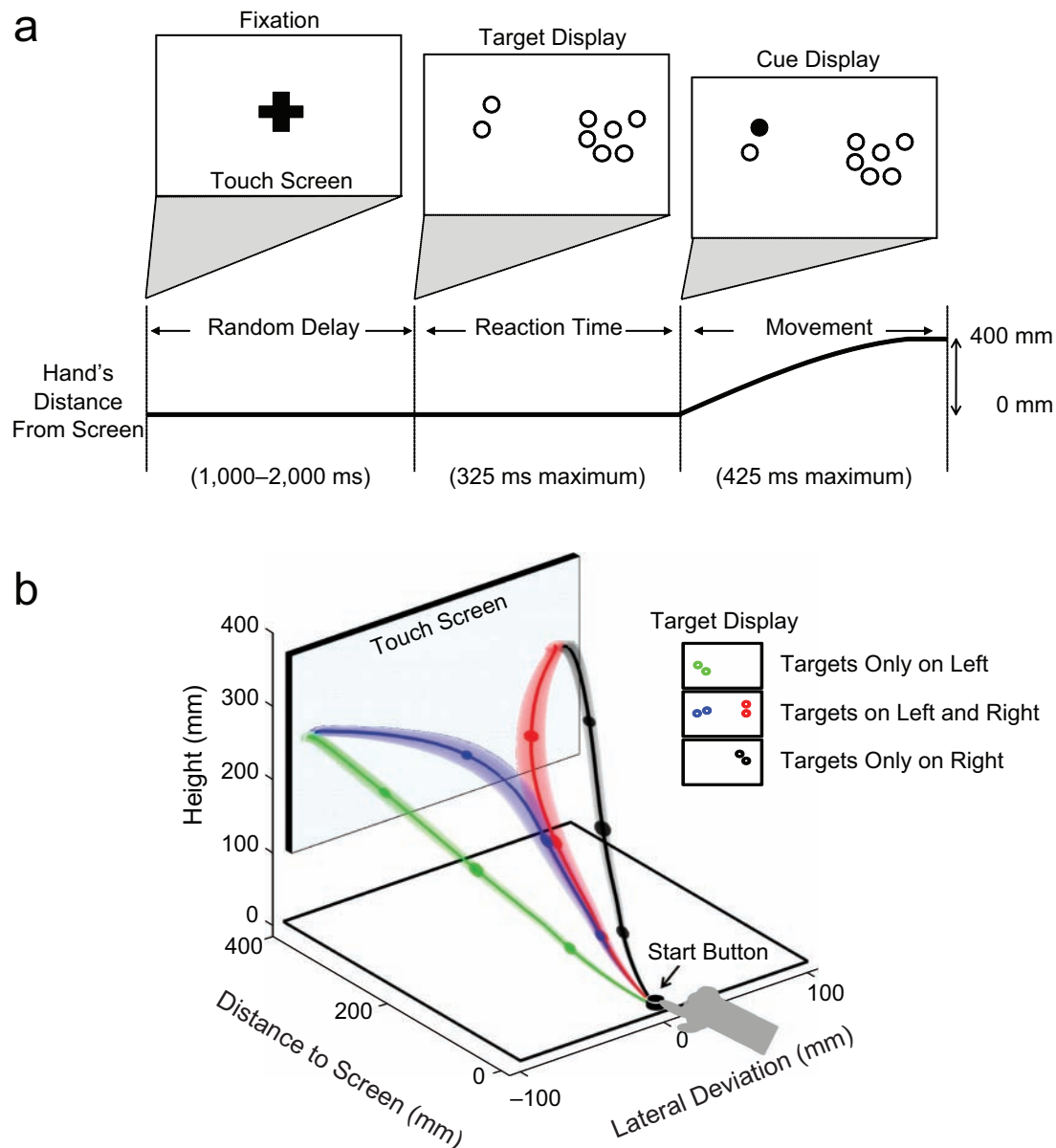


Fig. 1. Illustration of the task (a) and subjects' arm trajectory (b). Following the presentation of a fixation cross for a random interval between 1,000 ms and 2,000 ms, potential targets (unfilled circles) were displayed on the left, right, or both sides of a touch screen. Subjects were required to release a start button and, using the same finger, reach toward the target display within 325 ms. After subjects released the button, one of the targets in the display filled in black to cue subjects to correct their trajectory and touch the screen at that location within 425 ms. The diagram below the displays in (a) illustrates the linkage between the subject's movement and the onset of the cue display. The three-dimensional view of the experimental setup (b) shows reach trajectories for example target displays averaged across 22 subjects. When targets appeared on both the left and the right, the cue could be on either side of the display; in the examples shown here, the color coding indicates the side of the display on which the cue appeared. Shaded areas around the darker trajectories represent average standard errors; the darkened ovals indicate 25%, 50%, and 75% of movement distance, and their size is proportional to the velocity in the x, y, and z dimensions (colors are for purposes of illustration only).

differences in 2:1 through 2:4 displays and not to trajectory differences in 2:5 through 2:8 displays, we ran a linear post hoc comparison. We calculated the slope of two lines for each subject: The first line best fit his or her lateral position data on 2:1 to 2:4 displays, and the second line best fit his or her lateral position data on 2:5 to 2:8 displays. This analysis showed that

slopes for 2:1 through 2:4 displays were positive when the amount of targets increased, and slopes for 2:5 through 2:8 displays were either negative or showed no difference when the amount of targets increased. This confirmed our ANOVA results, and this pattern was almost identical regardless of whether reaches ended on the left or the right of the target display.

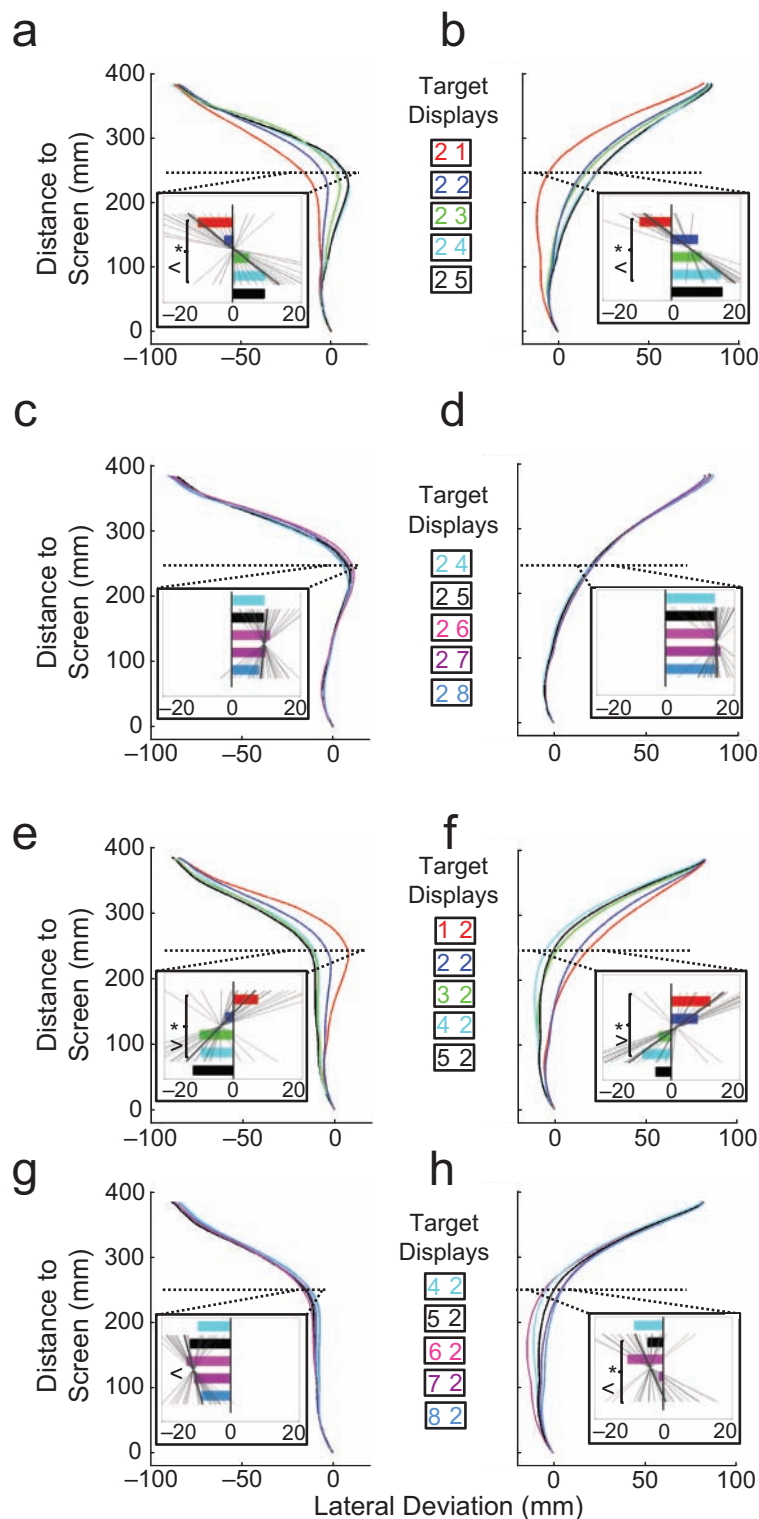


Fig. 2. Results from the main experiment: plots of overhead views of reach trajectories (lateral deviation from the start button vs. distance from the target display). Target displays consisted of clusters of circles: One side of the display had a constant number of targets (two), and the other side of the display had between zero and eight targets (i.e., the constant:variable ratio was between 2:0 and 2:8). The location of the constant group was randomly varied between the left (a–d) and right (e–h) side of the display. The cued target appeared either on the left (a, c, e, and g) or on the right (b, d, f, and h). Results are shown separately for ratios with smaller numbers of targets (first and third rows) and larger numbers of targets (second and fourth rows). For purposes of comparison, ratios with four and five targets on one side are included in all rows. Inset bar graphs show the lateral deviation of trajectories at 60% of mean reach distance, when subjects began to correct their reach toward the cued target. An asterisk denotes significant differences among the lateral deviations depicted in the bar graph (ANOVA, $p < .05$, Greenhouse-Geisser corrected). Thin lines depict regression slopes from each subject, and the thick dark line in each graph represents the averaged regression slope across all subjects. The “<” and “>” signs indicate that the slopes across individuals were less than and greater than 0, respectively ($p < .05$).

Although a diminishing influence of each additional target on the initial trajectory is in part expected in spatial averaging (as also predicted by Weber's Law; Weber, 1834/1996), the similarity of arm trajectories for target numbers greater than four is not adequately explained by this rationale. For instance, we found no significant differences between trajectories for 2:4 and 2:8 displays, in which the likelihood of reaching toward the right side of the display increased by 13%. Conversely, there were robust and significant differences between trajectories for 2:2 and 2:3 displays, in which the likelihood of reaching toward the right side of the display increased by only 10%. These findings are best explained as a capacity limit in the number of visual targets that can be simultaneously considered for action. Moreover, we also found that the saturation of arm trajectories for 2:5 through 2:8 displays was completely independent of the biomechanical constraints of the limb (as indicated by performance on baseline trials, see Fig. 1; also see Methods and Analyses, Fig. S2, in the Supplemental Material).

There are two important caveats to this interpretation of our main experiment. First, it is possible that the maximal trajectory bias observed when four items were presented on one side of the display may have reflected an inherent maximal trajectory bias or ceiling effect when the asymmetry in probability reached a specific threshold (e.g., 2:4, 67% probability of one side of the display being selected). Second, and more generally, because the number of targets displayed was tied to probability (i.e., the side of the display that contained more targets was more likely to be cued with a filled-in target), participants may simply have been attending to the size of the target display, and not to the target quantity, to plan their movements. To address these concerns, we ran two separate control experiments.

Ratio Control Experiment

If reach trajectories are maximally biased by a certain target ratio (e.g., 2:4), then exactly the same degree of deviation should occur for displays containing the same ratio but more targets (e.g., 4:8 and 8:16). In contrast, if subjects largely fail to enumerate targets beyond four, as our main experiment suggests, then there should be little or no deviation toward the higher target numbers in displays with more than four potential targets (i.e., 4:8 and 8:16). To explicitly test this hypothesis, we conducted a control experiment that held the probabilistic distribution (or target ratio) constant across several displays but manipulated the number of targets presented (see Fig. 3 for examples of target displays used; for a similar approach, see Revkin et al., 2008).

Method

Twenty-four naive right-handed subjects who had not participated in the main experiment performed in our ratio control experiment. All timing and criteria were exactly the same in the two experiments, with one major exception: We presented three display types: (a) biased displays, in which the number of

targets changed but their probabilistic distribution across both sides of the display was held constant: 1:2 or 2:1, 2:4 or 4:2, 4:8 or 8:4, 8:16 or 16:8; (b) equal displays: 1:1, 2:2, 4:4, 8:8, 16:16; and (c) baseline displays: 1:0 or 0:1, 2:0 or 0:2, 4:0 or 0:4, 8:0 or 0:8, 16:0 or 0:16. Subjects performed an initial training session of at least 88 trials followed by 440 test trials (separated across 10 blocks). (Additional information about the participants, stimuli, and procedures in this experiment can be found in Methods and Analyses in the Supplemental Material.)

Results

In our previous research, we found that the most robust method for measuring the bias introduced by target displays was to compare the lateral-deviation differences between trajectories toward the mirror version of target displays containing the same number of targets (i.e., 1:2 vs. 2:1, Chapman et al., 2010). Therefore, to directly test the prediction that there is a capacity limit of approximately four targets for visuomotor planning, we ran four a priori functional pair-wise comparisons between each mirrored pair of our biased displays (see Figs. 3a–3d; for a detailed explanation of this and other analyses conducted on data from this experiment, see Methods and Analyses in the Supplemental Material). The resulting deviation differences (with 95% confidence intervals) are directly compared in Figure 3e. It is important to note that in target displays containing two and four targets on one side (Figs. 3a and 3b), reach trajectories were deviated toward the higher number of targets (this deviation is also evident in that the difference between both trajectories diverged significantly from zero, Fig. 3e). It is critical to note, however, that for target displays containing eight targets on one side (4:8 and 8:4 displays, Fig. 3c), reach trajectories showed no reliable deviation toward the higher number of targets (the green trace in Fig. 3e is not significantly different from zero).

Unexpectedly, however, the results were reversed for displays containing 16 targets on one side (8:16 and 16:8 displays): Reach trajectories consistently deviated toward the lower number of targets (Fig. 3d). This seems paradoxical with respect to the probabilities inherent in the unequal target display and suggests that when rapidly enumerating sets of objects with more than eight items, other properties (like clustering and proximity) may affect the perceived number of items. This latter finding could provide an interesting avenue for further investigation. The important conclusion from this experiment, however, is that despite the target-ratio differences being constant across these four display types (1:2, 2:4, 4:8, and 8:16), when presented with more than four targets on one side of the display (i.e., 4:8 and 8:16), subjects appeared unable to sensibly use this additional target information to guide their movements.

Size Control Experiment

In the main and ratio control experiments, it is possible that participants' trajectories were being drawn toward the side of

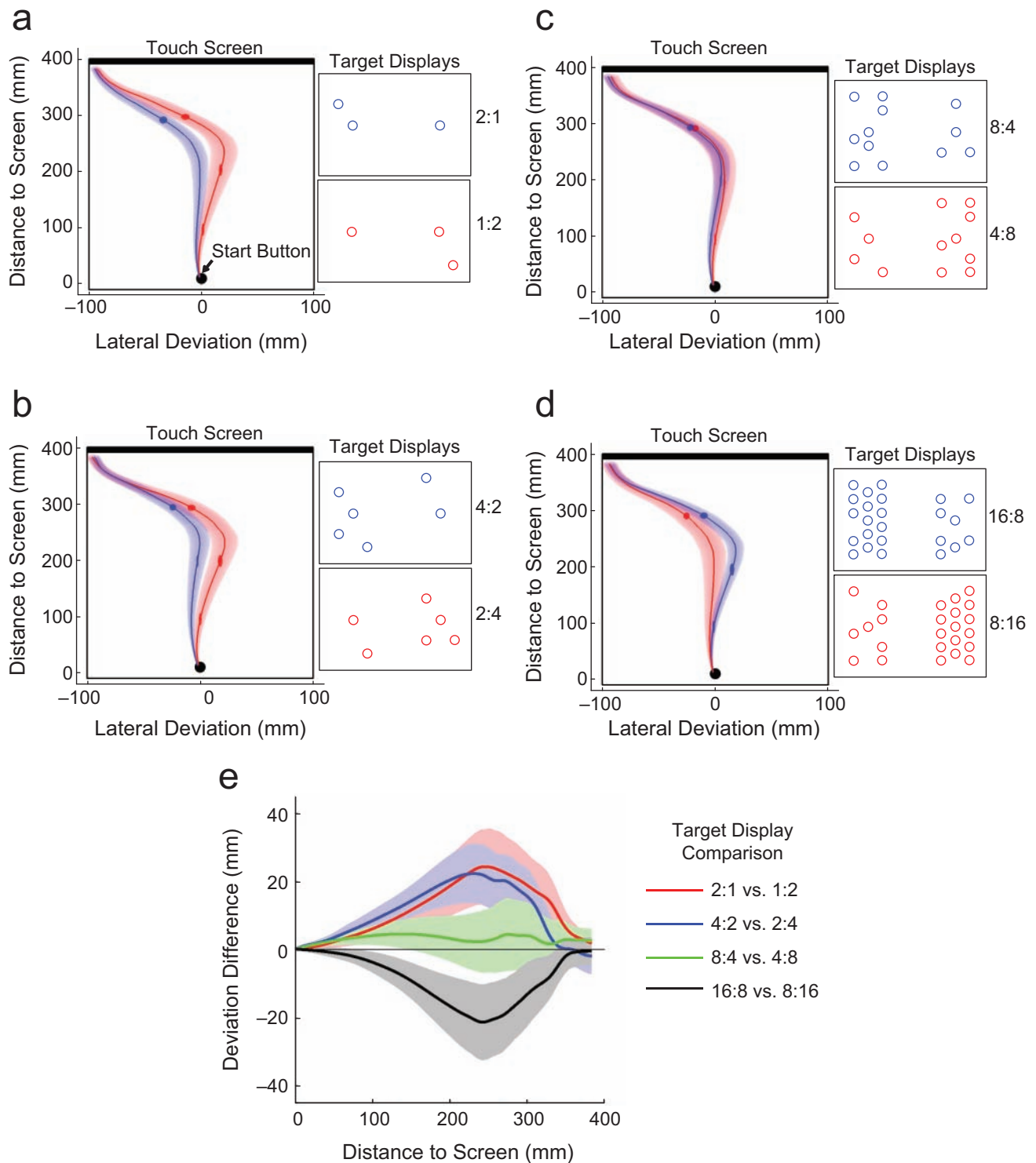


Fig. 3. Results from the ratio control experiment. The graphs in (a) through (d) show mean reach trajectories for target ratios of 2 to 1 and 1 to 2, but with increasing numbers of targets. Results are shown for trials on which targets on the left were cued. Light-shaded areas around the trajectory traces represent average standard errors; the darkened ovals indicate 25%, 50%, and 75% of movement distance, and their size is proportional to the velocity in the x and y dimensions. The dark colored lines graphed in (e) show the difference between the red and blue (red – blue) trajectory traces (i.e., the difference in lateral deviation between displays with more targets on the right and displays with more targets on the left) in the top four graphs as a function of distance from the screen. Shaded areas around the lines show 95% confidence intervals; colors are for purposes of illustration only.

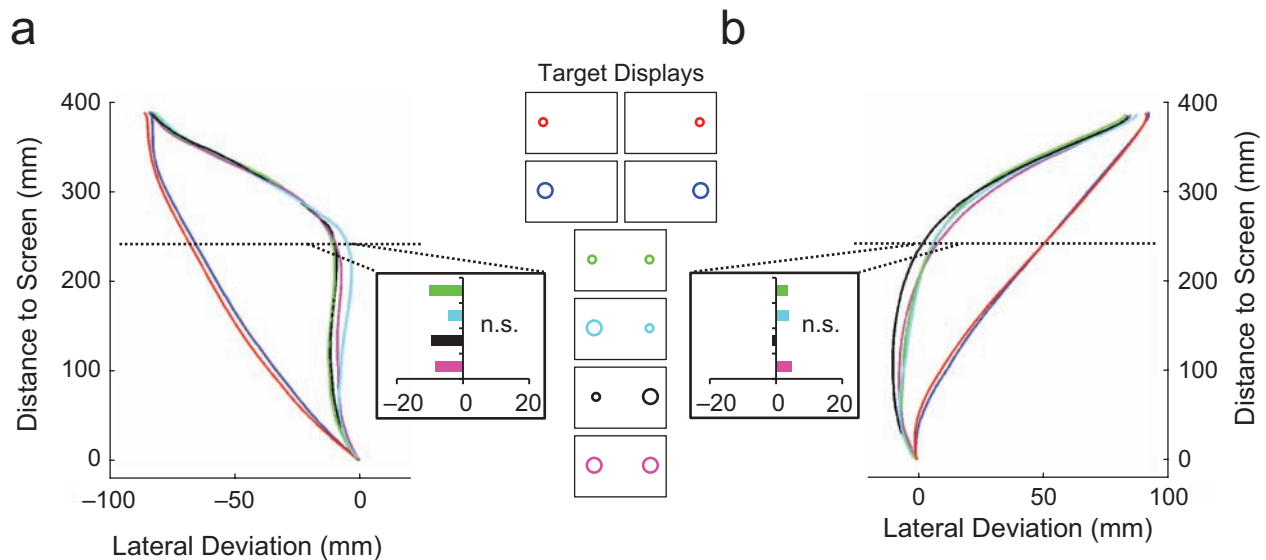


Fig. 4. Results from the size control experiment: averaged reach trajectories to single- and two-target displays containing two possible target sizes (large and small). Targets on the (a) left or (b) right side of the display were cued. The inset bar graphs show the lateral deviation of trajectories at 60% of mean reach distance, when subjects began to correct their reach toward the cued target (shown only for trials with targets on both sides of the display). The color coding in the target displays is for purposes of illustration only; in the experiment, all targets were outlined in black.

the display with the larger stimulus size (which increased with the number of potential targets) rather than just toward the side of the display with the larger number of targets per se. This account, of course, fails to explain the capacity limit observed in the ratio control experiment. Nevertheless, to rule out a simple effect of display size on reach trajectories, we conducted a second control experiment, which held constant the probability of acting on either side of the display (using a 1:1 display) but manipulated the size of individual targets (see Fig. 4 for target displays used). (Additional information about the participants, stimuli, and procedures in this experiment can be found in Methods and Analyses in the Supplemental Material.)

Method

Sixteen naive right-handed subjects who had not participated in the previous two experiments performed in our size control experiment. All timing and criteria were the same as in the previous two experiments, except that target displays contained either one target on the left or right side (1:0 or 0:1 displays) or two potential targets, one each on the left and right (1:1 display). The critical factor in this experiment was that each target could be either large or small. Large targets subtended the visual size of the entire cluster described in the main experiment (corresponding approximately to a diameter three times larger than that of small targets; see Methods and Analyses, Fig. S1, in the Supplemental Material). It is important to note that when a large target was cued, a circle only 2 cm in diameter at the center of the target filled in black; this procedure equated both the onset salience (the target filling in) and the precision requirements of the reach endpoint for small and large targets. Thus, any observed deviation of trajectories

toward large targets should reflect only movement-planning biases based on the visual size of the target prior to reach onset. Subjects performed an initial training session of at least 32 trials followed by 160 test trials.

Results

Using the same analysis employed in the main experiment (statistical rendering of the entire reach trajectory and examination of the lateral deviation of trajectories at 60% of reach distance), we found that movements in the size control experiment were not significantly biased toward the larger targets in 1:1 displays but instead aimed for a midpoint between target locations (Fig. 4; for a detailed explanation of this and other analyses conducted on data from this experiment, see Methods and Analyses in the Supplemental Material). This result is consistent with the hypothesis that two equally probable targets are simultaneously coded (Chapman et al., 2010) independently of their size.

General Discussion

Taken together, the results of the spatial-averaging behavior observed in these three experiments appear to be driven by multiple competing targets rather than by low-level visual target features. In addition, our results show that a processing limit of three to four items can be revealed in a continuous fashion through time-evolving movements and not just in discrete measurements (e.g., response times) as used in typical tasks (e.g., key presses, verbal reports). Moreover, in contrast with other previous measures (e.g., percentage of correct responses), the measures in our task also show that target enumeration (and its

capacity limits) is not even tied to the final choice made by the subject: Initial trajectories are influenced only by the probabilistic distribution of the number of targets in the display and not by which final target is cued during the subject's arm movement.

These results, to the best of our knowledge, are the first to show that the limits of parallel individuation and the selective processing of small numbers of items extend well beyond the boundaries of conscious processing and into the domain of nonconscious movement planning. This suggests that the visual enumeration processes engaged in action planning and explicit perceptual tasks rely on a common underlying mechanism. But what can our visuomotor results tell us about the nature of that mechanism?

Given the extremely short response latencies in striate visual cortex for stimulus detection (30–50 ms; Maunsell & Gibson, 1992) and that only a limited number of objects can compete for representation and attentional selection in the early visual system at a given time (e.g., Duncan, 2006; Pylyshyn, 1998), any vision-related bottleneck should subsequently constrain the downstream capacities of both perceptual and rapid visuomotor processing. The reports on capacity limits of attention, however, have remained largely within the domain of purely perceptual studies and tasks (Cowan, 2001; Franconeri, Alvarez, & Enns, 2007; Marois & Ivanoff, 2005), and little or no evidence has suggested that these limits can also pertain to visually guided behaviors. This is surprising, especially given that several lines of recent evidence show that perceptual processing is bidirectionally and causally interconnected with sensorimotor neural processes (e.g., premotor theory of attention; Moore, Armstrong, & Fallah, 2003; Moore & Fallah, 2001; Rizzolatti, Riggio, Dascola, & Umiltà, 1987).

From an ecological perspective, the direct link between action- and attention-related processes seems quite intuitive: The primary benefit of attentional processing, after all, is to influence incoming sensory information so as to bias the generation and guidance of behaviors—an important fact that is reflected in both the evolution and the development of sensorimotor systems. For instance, both semi-free-ranging monkeys and human infants are able to quantify up to three or four items accurately in action-decision tasks, but fail to differentiate items beyond that range in order to guide their selections (Feigenson, Dehaene, & Spelke, 2004; Hauser, Carey, & Hauser, 2000). It is important to note that in these studies with infants and monkeys, as in the current experiment, individuals are often required to make a decision between two separate sets of items. Although this means that participants can accurately differentiate total numbers of items greater than four (i.e., two items plus four items is actually six total items), we believe, as other researchers have suggested (Feigenson et al., 2004; Hauser et al., 2000), that the capacity limit of four items in a decision-making task represents the upper boundary on the accurate enumeration of each set individually.

The evident links between attention and sensorimotor control have prompted several researchers in psychology and neuroscience to expand their operational definition of visual

attention and to question whether using the term “visual” without some reference to its intimate links with motor output is sensible (Baldauf & Deubel, 2010; Cisek & Kalaska, 2010; Duncan, 2006). Indeed, on the basis of the capacity limit observed in the present research, we could speculate that primitive “number sense” might actually be evolutionarily rooted in the early attentional mechanisms supporting the nonconscious capacity limit of parallel visuomotor planning. This novel speculation provides an ecologically and behaviorally relevant suggestion as to why the enumeration of higher quantities (i.e., more than four items) requires the intervention of additional cognitive mechanisms, such as approximation and counting, necessitating serial shifts of attention (Dehaene, 1997; Kaufman et al., 1949; Luck & Vogel, 1997; Pylyshyn & Storm, 1988; Revkin et al., 2008). Moreover, this might also explain why the posterior parietal cortex—in particular, the intraparietal sulcus—is activated both in purely perceptual tasks requiring the simultaneous processing of multiple objects (e.g., multiple-object tracking; Culham, Cavanagh, & Kanwisher, 2001), visual short-term memory (Xu & Chun, 2009), and simple counting and enumeration (Ansari, 2008; Cohen Kadosh & Walsh, 2009) as well as in tasks requiring the planning and execution of motor movements (Andersen & Buneo, 2002; Goodale & Milner, 2004). After all, if selective attention toward multiple objects is equivalent to enhancing those objects' relevance as potential action goals, then the same brain areas should be recruited. This is exactly the interpretation of parietal-frontal circuitry that has been recently advanced by several researchers (e.g., Cisek & Kalaska, 2010; Duncan, 2006).

This framework provides specific predictions about the cognitive level at which targets were represented in the experimental task reported here—namely, it predicts that the visual selection of action-relevant targets occurs both automatically and outside of conscious awareness. Specific properties of our task appear to support this claim. For instance, our requirement that subjects initiate rapid motor movements (within 325 ms, but usually 230 ms on average and independent of the number of targets) after presentation of the target display makes it unlikely (if not impossible) that subjects consciously planned the reported adjustments in their initial trajectories in accordance with the probabilistic distribution of targets (cf. Andersen & Buneo, 2002; Goodale & Milner, 2004). This contrasts with how this same capacity limit emerges in perceptual tasks requiring conscious reports, such as rapid counting. In those tasks, reaction times are much slower than in our task (minimum 400 ms), and they scale with the number of items—showing a sharp increase for sets presented outside the subitizing range (e.g., an additional 40–100 ms per item for one to four items and an additional 250–350 ms per item beyond four; Trick & Pylyshyn, 1994).

The common capacity limit of three to four items observed in both conscious perceptual and visuomotor planning tasks (the latter reported in this article) points to a shared nonconscious attentional mechanism that rapidly filters incoming

sensory information on the basis of the combined visual and motor relevance of objects in the environment. Our findings offer a completely novel demonstration of the capacity limit of parallel individuation and suggest that this bottleneck reflects a more basic and fundamental limitation of parallel object processing in the brain.

Acknowledgments

The first two authors contributed equally to this work.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information may be found at <http://pss.sagepub.com/content/by/supplemental-data>

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