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Object width modulates object-based attentional selection

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Abstract

Visual input typically includes a myriad of objects, some of which are selected for further processing. While these objects vary in shape and size, most evidence supporting object-based guidance of attention is drawn from paradigms employing two identical objects. Importantly, object size is a readily perceived stimulus dimension, and whether it modulates the distribution of attention remains an open question. Across four experiments, the size of the objects in the display was manipulated in a modified version of the two-rectangle paradigm. In Experiment 1, two identical parallel rectangles of two sizes (thin or thick) were presented. Experiments 2–4 employed identical trapezoids (each having a thin and thick end), inverted in orientation. In the experiments, one end of an object was cued and participants performed either a T/L discrimination or a simple target-detection task. Combined results show that, in addition to the standard object-based attentional advantage, there was a further attentional benefit for processing information contained in the thick versus thin end of objects. Additionally, eye-tracking measures demonstrated increased saccade precision towards thick object ends, suggesting that Fitts's Law may play a role in object-based attentional shifts. Taken together, these results suggest that object-based attentional selection is modulated by object width.

Keywords Object-based attention · Eye movements and visual attention · Attention: Selective

Visual attention, the mechanism by which relevant and salient information is selected for further processing, is constrained by a multitude of factors including spatial (B. A. Eriksen & Eriksen, 1974; Posner, 1980; Posner, Snyder, & Davidson, 1980; Yantis & Johnston, 1990), feature (Baylis & Driver, 1992; Treisman & Gelade, 1980; Wolfe, 1994), and object-based (Duncan, 1984; Egly, Driver, & Rafal, 1994; Rock & Gutman, 1981; Shomstein, 2012) information. Most of the early research on object-based attentional selection sought to establish that object representations, in addition to space-based representations, influence attentional allocation (Behrmann, Zemel, & Mozer, 1998; Duncan, 1984; Egly et al., 1994; Kanwisher & Driver, 1992; Moore, Yantis, & Vaughan, 1998; Rock & Gutman, 1981; Watson & Kramer, 1999; for review, see Shomstein, 2012).

The most influential study of object-based attentional selection continues to be the two-rectangle paradigm developed by Egly, Driver, and Rafal (1994). In this paradigm, two identical parallel rectangles, oriented either vertically or horizontally, are presented to participants. After a brief delay, one end of one of the rectangles is cued by a brief illumination, engaging attention at the cued location. Following another short delay, a target is presented in one of three possible locations: the same location as the cue (*valid*), the opposite end of the cued rectangle (*invalid same object*), or at the same distance from the cue, but in the other rectangle (*invalid different object*). Two major findings are observed from this paradigm. First, consistent with theories of space-based selection, targets that appear in the validly cued location are detected faster and more accurately than targets that appear in any other location, demonstrating that the spatial distance between the cued location and the target affects the quality of the perceptual representation (Desimone & Duncan, 1995; Posner, 1980). The second finding is that targets presented in the invalid same-object location are detected faster and more accurately than those in the invalid different-object location, even though the spatial distance from the cue is equated. This within-object facilitation, labeled the object-based advantage, strongly suggests that attentional allocation is not constrained exclusively by the spatial distance between the target and the cued location, but by the representation of the object as well.

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While object-based attentional facilitation has mostly been examined in covert attentional allocation (i.e., orienting attention without eye movements), several studies have demonstrated that the same advantage is observed in overt shifts of attention involving eye movements. For instance, when saccades are necessary for target identification, participants are more likely to allocate attention from the cued location to the invalid same object than toward the invalid different object and are also faster at executing the corresponding saccades (McCarley, Kramer, & Peterson, 2002; Theeuwes, Mathot, & Kingstone, 2010). Using real-world scenes, Malcolm and Shomstein (2015) also found similar results, such that participants are faster at initiating a saccade toward a target embedded within a real-world scene if the target is within the boundaries of a cued object. Thus, not only do objects influence covert attentional shifts but overt attentional shifts as well, suggestive of similarities or carryover effects from perceptual to the motor system (Rizzolatti, Riggio, Dascola, & Umiltá, 1987)

Since the initial investigations of the robustness and replicability of object-based facilitation, research has focused on elucidating the mechanisms that give rise to this facilitation in attentional allocation (Chen & Cave, 2006, 2008; Drummond & Shomstein, 2010, 2013; Lamy & Egeth, 2002; Müller & Kleinschmidt, 2003; O'Craven, Downing, & Kanwisher, 1999; Shomstein & Yantis, 2002, 2004). One key finding is that the physical characteristics of an object influence the quality of object representations, and ultimately modulate the effect of objects on attention (Chen, 2012). For instance, the magnitude of the object-based advantage varies based on illusory boundaries and object contours (Avrahami, 1999; Marino & Scholl, 2005), the perceived length of an object (Robertson & Kim, 1999), illusory contours (Moore et al., 1998), amodal completion (Behrmann et al., 1998), bottom-up and top-down factors (Watson & Kramer, 1999), and the strength (salience) of object representations (Shomstein & Behrmann, 2008; see also Kravitz & Behrmann, 2011).

An important physical property that is notably missing from investigations of object properties that influence object-based attention allocation is that of object size. Size is an intrinsic attribute of all objects in the physical world, and its computation is inherently present given the retinotopic nature of visual processing in the ventral visual system (i.e., size of the retinal image and observer's distance; Baird, 1963; Hubbard, Kall, & Baird, 1989). Moreover, the observer's body is thought to serve as a "fundamental ruler," whereby the size of external objects is automatically perceived in relation to the size of the body (van der Hoort & Ehrsson, 2016). Representing the physical size of objects is also critical in determining how we interact with them (Gibson, 1979). For instance, smaller objects, such as coins and pens, but not larger objects, such as cars and buildings, are manipulated with hands and fingers. In light of the above, it is perhaps unsurprising that object size can act as a top-down attribute that influences attention (Treisman & Gormican, 1988; Wolfe & Horowitz, 2004) and can even serve as a means of bottom-up attentional capture (Proulx, 2010; Proulx & Egeth, 2008). Additionally, recent research has revealed that despite the ever-changing size of real-world objects due to the discrepancy in retinal image size, not only do objects have a canonical visual size (Konkle & Oliva, 2011), but the neural representations of objects can be differentiated based on size as well (Konkle & Oliva, 2012). Given the significant role that size plays in our daily lives, it is surprising that most investigations of object-based attention have employed objects of identical size, thereby precluding an evaluation of the contribution of this stimulus dimension to object-based attentional facilitation.

While the influence of an object's size on object-based attentional facilitation has not been thoroughly investigated, there is evidence suggesting that size does influence covert and overt attention (Castiello & Umiltà, 1990, 1992; C. W. Eriksen & St. James, 1986). Using a variant of the Posner spatial cueing paradigm, Castiello and Umiltà (1990) demonstrated that the attentional focus is more diffuse when targets are embedded within a large object and is more concentrated when targets are embedded in smaller objects. Thus, the results suggest that the efficiency of attentional processing is an inverse function of the size of attentional focus. The influence of size has also been the focus of substantial psychophysical research on motor movement. A well-known psychophysical principle, Fitts's law, proposes that the size of an object influences motor movements: When the distance between two objects is identical, faster but less precise movements are executed toward a wider as compared with narrower object (Fitts, 1954). Thus, the overall time to execute a movement is a function of the distance to and size of the object.

Decades of research has demonstrated a close link between the visual attention and motor systems (Colby & Goldberg, 1999). Voluntary motor movements such as saccades and hand movements are preceded by covert attentional shifts to the target location (Chelazzi et al., 1995; Godijn & Pratt, 2002; Kowler, Anderson, Dosher, & Blaser, 1995; McCarley et al., 2002; Tipper, Lortie, & Baylis, 1992) or to the object (Bekkering & Pratt, 2004). Behavioral evidence for the connection between visual attention and the motor system has also been reinforced by additional evidence from neuroimaging studies. For instance, fMRI studies have revealed that both covert and overt shifts of attention elicit responses in frontal eye field (FEF) and in the intraparietal sulcus (IPS) regions (Astafiev et al., 2003; Corbetta et al., 1998; de Haan, Morgan, & Rorden, 2008; Nobre, Gitelman, Dias, & Mesulam, 2000). Considering the close link between attention and movement planning, it is intuitive to hypothesize that object size might have a similar effect on covert attentional allocation involving objects as it does on voluntary motor movements to objects.

Here, in a set of four experiments, we examine directly the influence of object size on object-based attentional selection.

We hypothesized that the object-based influence on attentional selection will be modulated by object size (Wolfe & Horowitz, 2004). More specifically, if object-based attentional allocation is affected by size, as demonstrated by Castiello and Umiltà (1990), we would expect facilitation due to the higher fidelity of the attentional focus when attention is allocated to smaller objects compared with larger objects. However, if the effect of size on covert attentional shifts is similar to the effects within the motor movement system, we hypothesized faster covert attentional shifts toward large compared with small objects. Across four experiments engaging covert and overt attentional orienting, we demonstrate that attentional allocation is modulated by the size of the object to which attention is being allocated. More specifically, we consistently observed that covert and overt attentional shifts are facilitated by thicker objects (and thick ends of objects), suggesting that Fitts's law may also be applicable to covert attentional shifts.

Experiment 1: Rectangles

In Experiment 1, the two-rectangle paradigm (Egly et al., 1994) was modified to include objects of two different sizes. The size of the rectangles was manipulated by varying the objects' width while keeping other properties consistent. The goal of Experiment 1 was to investigate whether an object's size has consequences on the efficiency of attentional shifts both within and between objects. While object size has been shown to influence the size of the attentional focus (Castiello & Umiltà, 1990; Goldsmith & Yeari, 2003), how object size influences attentional shifts remains poorly understood. Previous research has demonstrated that large singletons as well as large objects capture attention in a bottom-up fashion during visual search (Proulx, 2010; Proulx & Egeth, 2008). Based on these findings, we hypothesized that an attentional benefit will be observed when an attentional shift occurs towards thicker compared with thinner objects. The effect of size on attentional shift may be additive, however, such that object-based attentional allocation per se is independent of size effects. Thus, object size will have an equal effect on shifts within and between objects. Alternatively, object size could have an interactive influence on object-based attentional shifts, in which case the magnitude of the effect of size may depend on whether the shift occurs within or between objects. This logic is also consistent with predictions from Fitts's law, such that faster attentional shifts will be observed toward larger than smaller objects.

Method

Participants Forty-one undergraduate students from Carnegie Mellon University participated in Experiment 1 in exchange for course credit. To demonstrate adequate power, a post-hoc power analysis was conducted using the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007) after data collection. Using a η^2 effect size (.502) taken from a previous study (Malcolm & Shomstein, 2015), the power analysis revealed that a sample size of $n = 16$ was sufficient to achieve the power of .999. All participants gave informed consent according to Carnegie Mellon University's institutional review board (IRB), were naïve to the purpose of the experiment, and all reported normal or corrected-to-normal vision.

Apparatus and stimuli The experiment was conducted in a dimly illuminated room with a monitor placed approximately 60 cm from the participant. All stimuli were presented on a dark gray background. The stimuli were either thin (width: 1 cm equivalent to 0.95°) or thick (width: 3 cm equivalent to 2.9°) black rectangles (see Fig. 1b). The lengths of all stimuli and the distance between the midpoints of the objects were 6 cm (5.7°; Fig. 1b) and the size of the targets and distractors was 0.38° × 0.67°.

Procedure At the start of each trial, two rectangles and a fixation cross were presented on a computer screen. After 1,000 ms, a red cue randomly but equiprobably highlighted one end of one object for 100 ms (see Fig. 1a). After a 100 ms interstimulus interval (ISI), participants detected the presence of a letter *T* or *L* embedded among nonletter *T/L* hybrid distractors similar to *T* or *L* while maintaining fixation. Two alternative forced-choice response was indicated by key press on the keyboard. The display was present for 2,000 ms or until a response was made. Validity was defined by whether the target appeared in the cued location (valid), at the opposite end of the cued object (invalid same object), or at the end of the uncued object nearest the cue (invalid different object). Valid trials comprised 60% of the total trials and the two invalidly cued locations occurred with an equal likelihood of 20% each. The orientation of the rectangle (horizontal, vertical) was a between-subjects factor, and object size (thin, thick) was manipulated within subjects with an equal number of trials for thin and thick rectangles in each block. Participants completed a total of 800 trials subdivided into 10 blocks of 80 trials.

Results and discussion

Participants with an overall target discrimination accuracy lower than 90% were removed from the analysis ($n = 9$) leaving a total of 32 participants in the final analysis (16 each in horizontal and vertical conditions). Response times (RT) faster than 250 ms (anticipatory responses) as well as RTs slower than 1,500 ms were removed as outliers (0.48% and 0.84%, respectively).

Space-based effects Space-based attentional effects were assessed by comparing validly cued versus invalidly cued

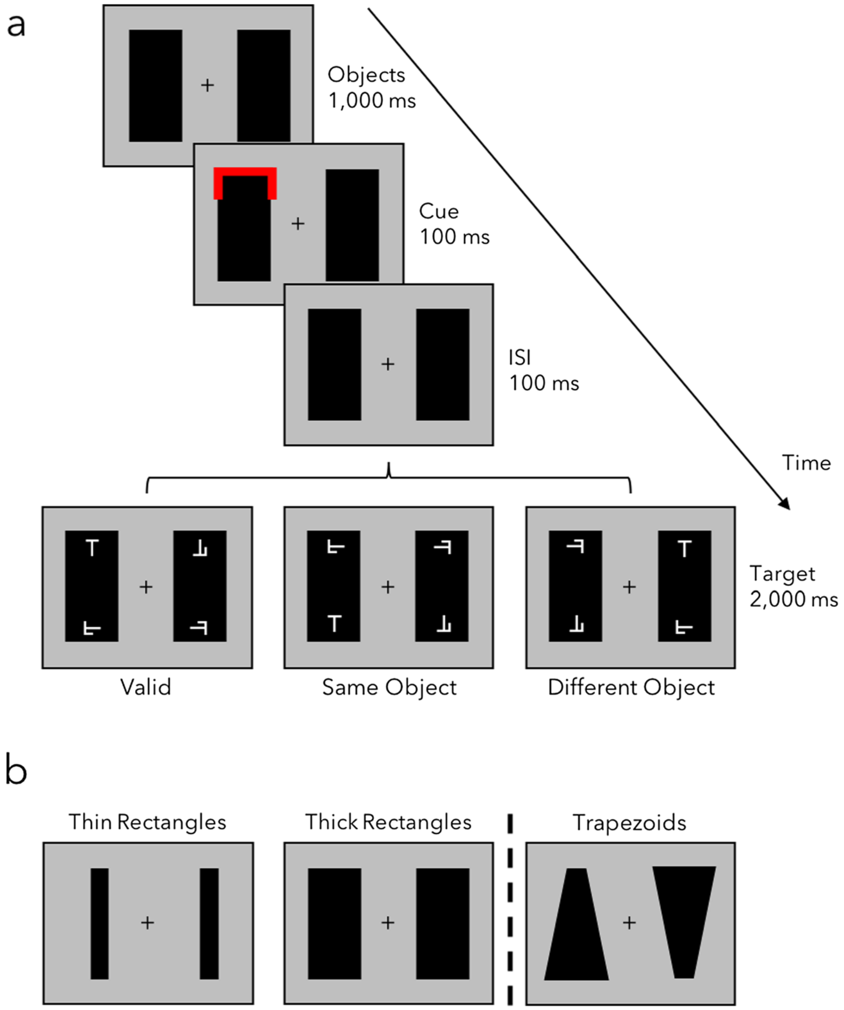

Fig. 1 Trial sequence in Experiment 1. This panel shows the thick rectangle condition (a). Sample display (b) of stimuli for Experiment 1 (left of dotted line) and Experiment 2–4 (right of dotted line)

trials (same object and different object). A three-way repeated-measures analysis of variance (ANOVA) with object validity (valid, invalid) and size (thick, thin) as within-subjects factors, and object orientation (horizontal, vertical) as a between-subjects factor was conducted for both accuracy and RT.

ANOVA conducted on accuracy revealed a significant main effect of validity, with overall higher accuracy in the valid (*M* = 96.32, *SE* = .41) than in the invalid condition (*M* = 93.88, *SE* = .50), $F(1, 31) = 53.47$ $p < .001$, $\eta_p^2 = .63$. No other main effects or interactions reached significance (*F*s < 1). ANOVA on RTs was conducted for correct responses only. A preliminary analysis revealed no significant main effect or interactions involving object orientation, and thus the data were collapsed across orientation for subsequent analyses (see Fig. 2). The ANOVA revealed a significant main effect of validity, with faster RTs for valid (*M* = 612.39 ms, *SE* = 5.19) than for invalid trials (*M* = 707.04 ms, *SE* = 5.09), $F(1, 31) = 153.62$, $p < .001$, $\eta_p^2 = .83$ (see Fig. 2a). There was also a significant validity × size interaction, $F(1, 31) = 15.03$, $p = .001$, $\eta_p^2 = .33$, such that validly cued targets that appeared in the end of the thin object (*M* = 609.82 ms, *SE* = 4.89) were identified faster that those appearing in the end of the thick object (*M* = 614.96 ms, *SE* = 5.52), $t(31) = 2.14$, $p = .040$. In the invalid condition, an opposite pattern was observed, with targets within the thick end of the object identified faster (*M* = 713.11 ms, *SE* = 4.69) than those within the thin end of the object (*M* = 700.96 ms, *SE* = 5.27), $t(31) = 3.26$, $p = .003$.

Object-based effects Object-based effects were assessed by comparing same-object and different-object invalidly cued trials. A two-way repeated-measures ANOVA with cued object (same object, different object) for invalidly cued targets and size (thin, thick) as within-subjects factors was conducted for both accuracy and RT.

ANOVA on accuracy did not reveal any significant main effects or interactions involving cued object or size (*F*s < 1). ANOVA on RTs was conducted for correct responses, revealing a significant main effect of cued object, $F(1, 31) = 39.51$, *p*

$< .001$, $\eta_p^2 = .56$. An object-based effect was observed, evidenced by faster target identification of the target in the invalid same-object (*M* = 692.08 ms, *SE* = 3.73) versus invalid different-object location (*M* = 721.96 ms, *SE* = 4.91). Consistent with our predictions, there was a significant main effect of size, $F(1, 31) = 11.01$, $p = .002$, $\eta_p^2 = .26$, with faster attentional shifts within or towards a thick object (*M* = 700.91 ms, *SE* = 4.69) compared with shifts of attention toward a thin object (*M* = 713.14 ms, *SE* = 5.27). There was no significant interaction between cued object and object size (*F*s < 1), suggesting that object size affected the within- and between-object attentional shifts additively and to a similar extent.

Experiment 1 examined whether an object's size modulates object-based attentional shifts. Both RT and accuracy results provide evidence for faster and more accurate target identification in the cued location. Interestingly, when participants executed an attentional shift (invalidly cued trials), object size affected attentional allocation in a manner predicted by Fitts's law—namely, targets in the thick object were correctly identified faster than those in the thin objects. However, for the valid trials, the pattern was reversed. This counterintuitive finding for the validly cued targets can potentially be driven by the size of attentional focus explanation originally proposed by Castiello and Umiltà (1990), such that in the validly cued targets that do not engage an attentional shift, a smaller focus of attention, induced by narrower objects, yields faster RTs. Thus, when attentional shift is required, participants exhibited significantly faster RTs toward thick rectangles compared with thin rectangles suggesting that Fitts' Law may extend to covert attentional shifts.

Experiment 2

Method

Experiment 1 demonstrated that object size modulates shifts of attention such that shifts within or between thick rectangles were faster than shifts within or between thin rectangles. However, while the objects used in Experiment 1 differed in width, the size of the starting and landing point of attention were kept constant (e.g., shifts involving thick rectangles always originated and terminated on thick rectangle ends). Thus, it is unclear whether the overall size of the object or the size of the landing point of attention was driving the size effect. Experiment 2 addressed this point by utilizing trapezoids (objects with ends of differing widths). With this manipulation, some attentional shifts originated from the thin end of an object and landed on the thick end, whereas others initiated on the thick end and landed on the thin end. If the size of the starting point influences attention, then the slower shift of attention to the narrow object could potentially be explained by the fact that the shift originates from the narrow object as well. The starting and the end point of attentional shifts are, thus far, confounded. If, using trapezoids, we observe faster shifts toward thick than thin ends of the objects, then we can conclude that the size of the destination of attention is driving the advantage for the thick over the thin objects. On the other hand, if a reversed size effect (faster shifts towards thin than thick objects) is observed, the size of the origin of attention is likely driving the effect of size.

Participants Thirty-five undergraduate students from Carnegie Mellon University participated in Experiment 2 in exchange for course credit. All students gave informed consent according to Carnegie Mellon University's Institutional Review Board, were naïve to the purpose of the experiment, and all reported normal or corrected-to-normal vision.

Apparatus and stimuli Experiment 2 was identical to Experiment 1, with the exception that stimuli were pairs of black trapezoids positioned in opposite orientations (see Fig. 1b). The thin end of the trapezoids was 1 cm wide and the thick end was 3 cm wide (sizes matched to the thick and thin rectangles used in Experiment 1). The lengths of all stimuli and the distance between the midpoints of the objects were maintained at 6 cm.

Procedure The procedure for Experiment 2 was identical to that in Experiment 1.

Results and discussion

Four participants with an overall accuracy lower than 90% were removed from the analysis, leaving a total of 31 participants in the final analysis (16 in horizontal and 15 in vertical condition). The criteria for removal of outliers were identical to Experiment 1, resulting in removal of 1.10 % of all trials.

Space-based effects A three-way repeated-measures ANOVA, with object validity (valid, invalid) and size of trapezoid end where target appeared (thick, thin) as within-subjects factors, and object orientation (horizontal, vertical) as a between-subjects factor, was conducted for both accuracy and RT. No interaction involving object orientation was observed for either RT or accuracy, and hence the data are collapsed across this factor.

ANOVA conducted on accuracy revealed a significant main effect of validity, with overall higher accuracy in the valid (*M* = 96.94, *SE* = .31) than in the invalid (*M* = 94.75, *SE* = .58) condition, $F(1, 31) = 21.62$, $p < .001$, $\eta_p^2 = .42$. No other main effects or interactions reached significance, (*F*s < 1). ANOVA on RTs was conducted for correct responses only. There was a significant main effect of validity, with faster RTs for valid (*M* = 625.62 ms, *SE* = 5.93) than for invalid (*M* = 714.78 ms, *SE* = 4.37) trials, $F(1, 30) = 121.27$, $p < .001$, $\eta_p^2 =$

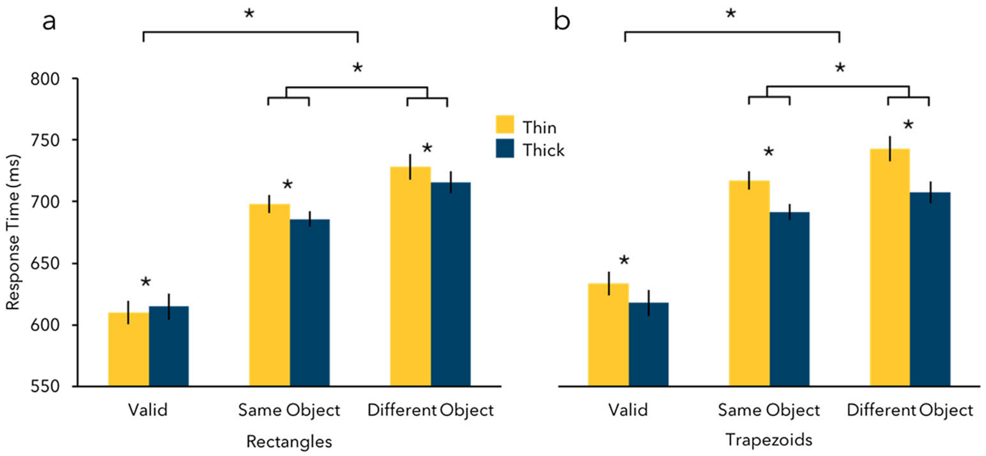

Fig. 2 Results for (a) Experiment 1 (rectangles) and (b) Experiment 2 (trapezoids). Attentional shifts, in both experiments, show faster target identification in thick ends of the objects. Error bars here and in all subsequent figures represent within-participant standard error of the mean (Cousineau, 2005)

.80. There was also a significant main effect of size, with faster RTs for targets that appeared in the thick end of the object (*M* = 658.76, *SE* = 8.33) than targets that appeared in the thin end of the object (*M* = 681.64, *SE* = 9.86), *F*(1, 30) = 45.26, $p < .001$, $\eta_p^2 = .60$. Last, there was a significant validity × size interaction, *F*(1, 30) = 7.79, $p = .009$, $\eta_p^2 = .21$. In the valid condition, targets that appeared in the thick end of the object (*M* = 617.76 ms, *SE* = 5.37) were identified faster than those appearing in the thin end of the object (*M* = 633.49, *SE* = 6.21), *t*(30) = 3.69, $p = .001$, a finding that differs from that observed in Experiment 1. In the invalid condition, targets appearing in the thick end of the object were identified faster (*M* = 699.75 ms, *SE* = 4.14) than those appearing in the thin end (*M* = 729.80 ms, *SE* = 5.06), *t*(30) = 7.06, $p < .001$, a replication of the effect also observed in Experiment 1.

Object-based effects Object-based effects were assessed by comparing same-object and different-object invalidly cued trials. A two-way repeated-measures ANOVA, with cued object (same object, different object) for invalidly cued targets and size (thin, thick) as within-subjects factors was conducted for both accuracy and RT.

ANOVA on accuracy did not reveal any significant main effects or interaction (*F*s < 1). ANOVA on RTs was conducted only for correct trials. A two-way repeated-measures ANOVA revealed a significant main effect of cued object, *F*(1,30) = 32.72, $p < .001$, $\eta_p^2 = .52$, with faster target identification in the invalid same-object (*M* = 704.48 ms, *SE* = 4.60) compared with a different-object (*M* = 725.32 ms, *SE* = 5.56) location. Importantly, there was again a significant main effect of size, *F*(1, 30) = 51.72, $p < .001$, $\eta_p^2 = .63$, with faster attentional shifts toward the thick end of the trapezoid (*M* = 699.71 ms, *SE* = 4.14) as compared with shifts of attention toward the thin end of the trapezoid (*M* = 730.09 ms, *SE* = 5.06). There was no significant interaction between cued object and object size, *F*(1, 30) = 2.13, $p = .155$ (see Fig. 2).

Experiment 2 examined whether the size of the starting or landing point of attention modulates object-based attentional shifts. The results demonstrate that attentional shifts toward the thick end of the trapezoid (both for within-object and between-object shifts) were significantly faster than the corresponding shifts toward the thin end, suggesting that it is the size of the landing point of attention that influences attentional shifts. If the size of the starting point was what influenced attentional shifts, we would have expected to observe the opposite results: faster shifts of attention that originate from the thick and thus land on the thin end. To check whether the magnitude of the size effect differed between experiments, a three-way mixed ANOVA with cued object (same object, different object) and size (thick, thin) as within-subjects factors and experiment (1, 2) as a between-subjects factor was conducted. If the size of the origin of attention was facilitating the size effect, we would expect to see an interaction between two experiments. Conversely, if the landing point of the attentional shift was driving the size effect, we would not expect to see an interaction. The ANOVA did not reveal a significant interaction with experiment (*F*s < *1*), thus providing support for the finding that the landing position or destination of the to-be-executed attentional shift is driving the effect of size on attentional allocation.

It should be noted that while the results of Experiment 2 replicated the effect of size on object-based shifts of attention, the effect of size on target identification within an already attended location (valid condition) was different between the two experiments. We do not have an obvious explanation as to why targets appearing in the cued thin end of the object in the rectangle experiment are identified faster, while targets appearing in the cued thin ends of trapezoidal objects are identified more slowly (as compared with thick ends). Given that this finding was not the main focus of our investigation (and the experiments were conducted between subjects), and that our interest is how object size influences shifts of attention, we point out this inconsistency and hope that it can be addressed by future research.

Experiment 3

Although the results of Experiment 1 and Experiment 2 demonstrate that attentional shifts towards the thicker versus thinner end of an object are faster, a possible alternative explanation is that target identification is simply easier in the thick object, as compared with the thin object. This explanation is similar in logic to the effects of crowding (Strasburger, Harvey, & Rentschler, 1991). On this account, the boundaries of the thin objects (at destination) might interfere with target processing to a greater degree than when the same boundaries are further away from the to-be-identified target, as is the case for thick objects. For crowding to be a possible explanation, the effect of size should also be observed in the valid condition where no attentional shift is required. However, the effect of size was inconsistent in the valid conditions across Experiments 1 and 2 such that the participants responded at a faster rate when targets appeared in the validly cued thin end of the object in Experiment 1 and faster toward the validly cued thick end in Experiment 2. To address these inconsistencies, Experiment 3 was designed to minimize the possible influence of object contours. In Experiment 3a, a target-detection task was used in place of a target identification task. Previous work has demonstrated that crowding mainly affects target identification rather than simple detection (He, Cavanagh, & Intriligator, 1997; Livne & Sagi, 2007; Pelli, Palomares, & Majaj, 2004), thus if the effect of size persists using a detection task, it would argue against the crowding explanation. In Experiment 3b, in a further attempt to reduce possible crowding effects, object boundaries were completely removed (i.e., the object contours were offset) prior to the onset of the search array. Removing the object contours at the time of target presentation would therefore eliminate any possible lateral inhibition from the object boundaries and provide a clear conclusion regarding target detection in larger versus smaller objects.

Experiment 3a: Target detection

Method

Subjects Thirty undergraduate students (19 female) from The George Washington University participated in Experiment 3 in exchange for experimental credit. Participants ranged in age from 18 to 20 years (*M* = 19.07 years), all reported normal or corrected-to-normal vision and were naïve to the purpose of the experiment. All experimental procedures were approved by The George Washington University's Institutional Review Board.

Apparatus and stimuli The experiment was identical to that of Experiment 2.

Procedure The overall procedure for Experiment 3 was identical to Experiment 2, except for three aspects. First, instead of a target identification task, participants performed a simple target-detection task by pressing the space bar when a white target square (0.77° × 0.77°) appeared (and it did so only at one end of the trapezoids). The thin end of the trapezoid was 1 cm wide (0.95°) and the thick end was 3 cm wide (2.90°). Second, participants completed a total of 880 trials subdivided into 10 blocks of 88 trials. Finally, valid trials comprised 55% of the total trials, the two invalidly cued locations occurred with an equal likelihood of 18% each, and catch trials comprised 9% of the total trials. Catch trials were included to prevent participants responding aimlessly and were used as a participant removal criterion.

Results and discussion

Participants with a false-alarm rate of over 30% were excluded ($n = 9$), leaving 21 participants in the final analysis (eight in horizontal). All participants met the 90% accuracy threshold for inclusion. Only RTs for correct responses (hits) were analyzed. RTs faster than 150 ms (interpreted as anticipatory responses) were removed from the analysis (11.73 %) and all RTs greater than 1,000 ms (0.25 %) were removed as outliers. A preliminary omnibus analysis with object size, object orientation, and validity demonstrated no main effects or interactions involving object orientation and, thus, the data were collapsed across orientation for subsequent analyses.

Space-based effect A two-way ANOVA, with object validity (valid, invalid) and size (thin, thick) as within-subjects factors, was conducted. There was a main effect of object validity, revealing that RTs were significantly faster, on average, for valid trials ($M = 313.44$ ms, $SE = 1.36$) than for invalid trials ($M = 317.93$ ms, $SE = 2.27$), $F(1, 20) = 33.92$, $p < .001$, $\eta_p^2 = .63$ (see Fig. 3). There was also a main effect of size, revealing that RTs were significantly faster, on average, when the target appeared on the thick end ($M = 314.61$, $SE = 2.10$) versus the thin end ($M = 316.76$, $SE = 2.00$) of the object, $F(1, 20) = 9.28$, $p = .006$, $\eta_p^2 = .32$. There was no significant interaction of validity by size ($F < 1$).

Object-based effect A two-way repeated-measures ANOVA on RTs, with cued object (same object, different object) for invalidly cued targets and size (thin, thick) as within-subjects

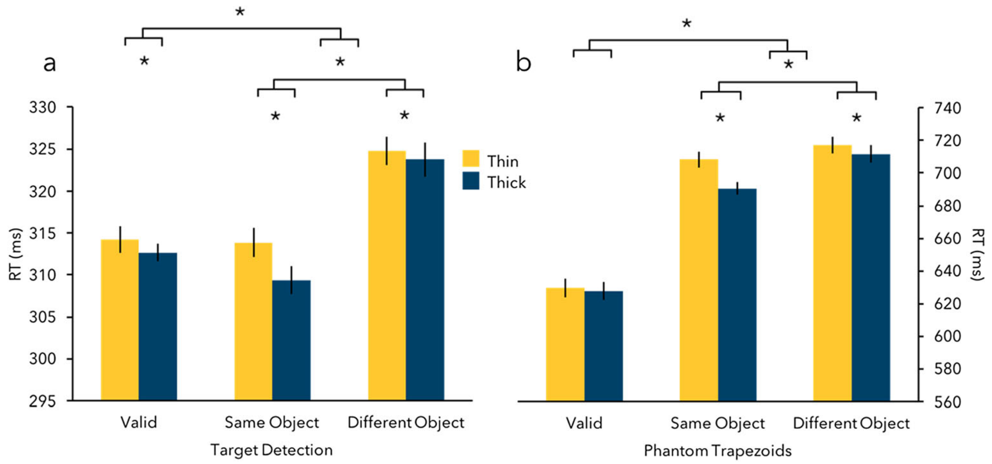

Fig. 3 Results for (a) Experiment 3a (target detection) and (b) Experiment 3b (phantom trapezoids). Attentional shifts, in both experiments, again show faster target detection/identification in thick ends of the objects

factors revealed a significant main effect of cued object, $F(1, 20) = 302.06$, $p < .001$, $\eta_p^2 = .94$. The object-based effect was observed, evidenced by faster target detection in an invalid same-object ($M = 311.57$ ms, $SE = 1.74$) compared with an invalid different-object location ($M = 324.31$ ms, $SE = 1.88$). Replicating the results of the previous two experiments, there was also a significant main effect of size, $F(1, 20) = 4.52$, $p = .046$, $\eta_p^2 = .18$., with significantly faster attentional shifts within or between thick ends ($M = 316.55$ ms, $SE = 2.44$) than the corresponding shifts of attention involving thin ends ($M = 319.31$ ms, $SE = 2.08$) of objects. There was no significant interaction between cued object and object size, $F(1, 20) = 1.49$, $p = .236$.

Experiment 3a examined whether a consistent effect of size can be observed even when the potential confounding influence from object contours was diminished. To achieve such an effect, participants no longer had to discern the identity of a letter target but instead responded simply whenever a probe target square appeared within the object boundary. Even with this change, participants were significantly faster at responding to the target when it appeared on the thicker compared with thinner end of the trapezoid. A cross-experiment ANOVA, with cued object and size as within-subjects factors, and experiment (2, 3a) as a between-subjects factor, did not reveal a significant interaction with experiment type ($F < 1$), suggesting that the size effect was consistent across experiments for attentional shifts within or between objects. Similar to Experiment 2, however, there was a main effect of size observed in the valid condition. To investigate whether the target-detection task reduced the potential influence from object boundary, a cross-experiment ANOVA on valid trials only, with size as a within-subjects factor and experiment (2, 3a) as a between-subjects factor revealed a significant interaction, $F(1,50) = 7.27$, $p = .01$, $\eta_p^2 = 13$. Further t tests revealed that the effect of size in the valid condition was only significant in Experiment 2, $t(31) = 2.14$, $p = .04$, and there was no effect of size in the valid condition of Experiment 3a. This provides evidence that the detection task implemented in Experiment 3a indeed reduced any potential contribution from crowding—something that we would have observed in the valid condition.

Experiment 3b: Phantom trapezoids

Method

Subjects Thirty undergraduate students from Carnegie Mellon University participated in Experiment 3b in exchange for course credit. All students gave informed consent according to Carnegie Mellon University's Institutional Review Board, were naïve to the purpose of the experiment, and all reported normal or corrected-to-normal vision.

Apparatus and stimuli The experiment was identical to that of Experiment 2.

Procedure The overall procedure for Experiment 3 was identical to that of Experiment 2, except for one aspect: The trapezoids disappeared (were offset) at the onset of the search array. As the trapezoids and target never appeared simultaneously, bottom-up influence from the former on the latter was mitigated.

Results and discussion

Four participants with an overall accuracy lower than 90% were removed from the analysis, leaving a total of 26 participants in the final analysis (13 in horizontal). The criteria for the removal of outliers were identical to Experiment 1, resulting in the removal of 0.62 % of the trials.

Space-based effects A three-way repeated-measures analysis of variance (ANOVA), with object validity (valid, invalid), and size (thick, thin), as within-subject factors, and object orientation (horizontal, vertical) as a between-subject factor, was conducted for both accuracy and RT. All data were collapsed across object orientation, as no significant interaction or main effect was observed for either dependent measure, *F*s < 1.

ANOVA on accuracy revealed a significant main effect of validity, with overall greater accuracy in the valid (*M* = 96.86, *SE* = .35) than in the invalid (*M* = 94.06, *SE* = .41) condition, $F(1, 25) = 61.43$, $p < .001$, $\eta_p^2 = .71$. The main effect of size did not reach significance, $F(1, 25) = 1.02$, $p = .32$, nor was there a significant Validity × Size interaction, $F(1, 25) = 3.04$, $p = .093$. ANOVA on RTs was conducted for correct responses only. There was a significant main effect of validity, with faster RTs for valid (*M* = 628.55 ms, *SE* = 5.59) than for invalid (*M* = 706.99 ms, *SE* = 5.26) trials, $F(1, 25) = 90.26$, $p < .001$, $\eta_p^2 = .78$. There was also a significant main effect of size, with faster RTs for targets that appeared in the thick (*M* = 676.72, *SE* = 8.63) than in the thin (*M* = 684.97, *SE* = 9.40) end of the object, $F(1, 25) = 5.80$, p = .024, $\eta_p^2 = .19$. Lastly, there was a significant validity × size interaction, $F(1, 25) = 5.00$, $p = .035$, $\eta_p^2 = .17$. In the valid condition, there was no significant difference between the RTs for targets that appeared in the thick (*M* = 627.7 ms, *SE* = 5.42) or thin end (*M* = 629.42, *SE* = 5.82) of the object, $t < 1$. In the invalid condition, however, targets appearing in the thick end of the object (*M* = 701.10, *SE* = 4.88) were identified significantly faster than targets appearing in the thin end of the object (*M* = 712.74, *SE* = 4.59), $t(25) = 2.66$, $p = .013$.

Object-based effects Object-based effects were assessed by comparing same-object and different-object invalidly cued trials. A two-way repeated-measures ANOVA, with cued object (same object, different object) for invalidly cued targets, and size (thin, thick) as within-subjects factors, was conducted for both accuracy and RT.

ANOVA on accuracies did not reveal any significant main effect or interactions (*F*s < 1). ANOVA on RTs was conducted only for correct trials. A two-way repeated-measures ANOVA revealed a significant main effect of cued object, $F(1, 25) = 6.75$, $p = .015$, $\eta_p^2 = .21$. An object-based effect was observed, evidenced by faster target identification in an invalid same-object (*M* = 699.51 ms, *SE* = 4.83) compared with a different-object (*M* = 714.47 ms, *SE* = 5.30) location. Importantly, there was again a significant main effect of size, $F(1, 25) = 6.93$, $p = .014$, $\eta_p^2 = .22$, with faster attentional shifts toward the thick end of the trapezoid (*M* = 701.23 ms, *SE* = 5.22) as compared with shifts of attention toward the thin end of the trapezoid (*M* = 712.75 ms, *SE* = 5.09). There was no significant interaction between cued object and object size, $F(1, 25) = 2.32$, $p = .14$ (see Fig. 3b).

To further control for the crowding explanation, in Experiment 3b, the objects were removed from the screen at the time of target presentation. This change allowed participants to perform the task without interference from object properties such as the boundaries or the surface. Despite the objects no longer being present on the screen at the time of target search and subsequent identification, the effect of the object representation as well as object width persisted. Consistent with the results from Experiments 1–3a, participants were significantly faster at responding to the target when it appeared on the previously seen thicker compared with thinner end of the trapezoid. The effect of size was not observed in the valid condition, where no attentional shift was required, but only observed in the invalid conditions when an attentional shift was necessary. The absence of the size effect in the valid condition, provides further support for the argument that the effect of size is not merely a consequence of interference from low-level object properties such as boundaries or contours but is, rather, a result of object size affecting the speed of attentional shifts.

Experiment 4

Across three experiments, object size influenced object-based attentional shifts, such that shifts were faster within or between thicker objects as compared with thinner objects. As noted in the introduction, size has been considered to be a visual attribute that guides attentional allocation. For instance, both physically (Proulx, 2010) and perceptually (Proulx, 2010; Proulx & Egeth, 2008; Proulx & Green, 2011) large task-irrelevant objects can capture attention in visual search. In line with these findings, we have provided evidence that an object's size also influences shifting of attention both within and between objects.

Mechanistically, one possible explanation for the influence of object size on attentional shifts can be offered by drawing parallels between attentional selection and motor control. Fitts's law, a well-established psychophysical principle, states that an object's width and the distance between two objects constrain movement time. More specifically, when distance is kept constant, faster physical movements are observed between two thick objects than between two thin objects (Fitts, 1954). Fitts's law has been demonstrated not only in overtly executed movements but also in imagined movements (Decety & Jeannerod, 1995) and observed movements (Grosjean, Shiffrar, & Knoblich, 2007). Given that Fitts's law also applies to saccades (Wu, Kwon, & Kowler, 2010), Fitts's law may apply to attentional shifts, as well.

To elucidate parallel constraints on attentional control and those evinced by the motor system, in Experiment 4 we did not require that subjects fixate centrally and, instead, tracked their eye movements to examine directly whether an object's size influences overt attentional shifts (saccades). Since previous research has demonstrated that object representations influence overt attentional allocation (McCarley et al., 2002; Malcolm & Shomstein, 2015; Theeuwes et al., 2010) and considering the close link between attention and the oculomotor system (Deubel & Schneider, 1996; Godijn & Theeuwes, 2003; Van der Stigchel & Theeuwes, 2007), we hypothesized that the influence of an object's size on covert attentional shifts, as shown in the first three experiments, would also be observed in saccadic movements as well. If Fitts's law also applies to overt shifts of attention, we predicted that participants would make more accurate saccades to thicker than thinner ends of objects regardless of whether the shift occurred within an object or between objects.

Method

Subjects Sixteen undergraduate students (13 female) from The George Washington University participated in Experiment 4 in exchange for experimental credit. Participants ranged in age from 18 to 28 years (*M* = 20.19 years), all reported normal or corrected-to-normal vision and were naïve to the purpose of the experiment. All experimental procedures were approved by The George Washington University's Institutional Review Board.

Apparatus and stimuli Stimuli were presented on a 21-inch ViewSonic G225f CRT monitor (ViewSonic, London, UK) positioned 55 cm from participants with a 140-Hz refresh rate. Participants sat with their head in a chin rest and made responses using a keyboard. Eye movements were recorded with an SR Research EyeLink 1000 (SR Research; Mississauga, Ontario, Canada), sampling monocularly at a rate of 500 Hz. The stimuli used in the current experiment were identical to those in Experiment 2. The only modification was the size of the targets and distractors. The size of the target and distractors (0.19° × 0.18°) was reduced significantly to ensure that a saccade was necessary in order to perform the task successfully.

Procedure The procedure for Experiment 4 was identical to that of Experiment 2, except for the following. A 5-point gaze accuracy calibration and validation test was conducted at the beginning of each experiment. After successful calibration and validation, the eye that tracked with more accurate spatial resolution, as determined by the EyeLink software, was selected for recording. Participants were required to fixate at the center dot for 300 ms for the trial to begin. When performing the *T/L* discrimination task, participants were asked to break fixation and actively locate and identify the target. Target size was deliberately selected such that identification was impossible without a direct fixation. The display was present for 3,000 ms (longer than previously to permit participants to locate the small target) or until a response was made. If participants broke fixation prior to the offset of the cue, the trial canceled out and was recycled within each block. Eye tracking was monitored by the experimenter throughout the entirety of the experiment and recalibrated when participants showed substantial drift in gaze position, preventing them from progressing to the next trial.

Results and discussion

Behavioral data Analysis was conducted for both accuracy and RT. Only RTs for correct responses were analyzed. All RTs greater than 2,500 ms (0.82%) were removed as outliers.

Space-based effects A three-way repeated-measures ANOVA, with object validity (valid, invalid) and size (thick, thin) as within-subject measures, and object orientation (horizontal, vertical) as a between-subjects measure, was conducted for both accuracy and RT.

ANOVA on accuracies did not reveal any significant main effects or interaction (*F*s < 1). ANOVA on RTs was conducted for correct responses only. A preliminary analysis revealed no significant main effect or interactions involving object orientation, thus the data were collapsed across orientation for subsequent analyses. ANOVA revealed a significant main effect of validity, with significantly faster RTs, on average, for valid (*M* = 957.13 ms, *SE* = 23.31) than invalid (*M* = 1221.92 ms, *SE* = 24.24) trials, $F(1, 15) = 66.21$, $p < .001$, $\eta_p^2 = .82$. A two-way repeated-measures ANOVA with cued object (same object, different object) for invalidly cued targets and size (thin, thick) as within-subjects factors revealed a significant main effect of cued object, $F(1, 15) = 12.60$, $p = .003$, $\eta_p^2 = .46$: participants were faster at identifying a target in the invalid same-object (*M* = 1184.83 ms, *SE* = 16.66) than in the invalid different-object (*M* = 1259.53, *SE* = 27.14) location, replicating the object-based effect in the previous three experiments. No other interaction or main effect reached significance (*F*s < 1).

Last fixation precision The precision of the last fixation was measured by calculating the distance between the center of the target and the center of the last fixation (in visual angle), where a lower value represents a more accurate fixation on the target. If the size of the object influences oculomotor movements, it is expected that participants will make more accurate saccades toward the thick than thin end of the trapezoids. A two-way repeated-measures ANOVA with cued object (same object, different object) and size (thin, thick) as within-subjects factors was conducted on fixation distance. There was a main effect of cued object, $F(1, 15) = 5.08$, $p = .040$, $\eta_p^2 = .25$; participants more were precise at fixating on a target when located within the cued (*M* = .87°, *SE* = .03) than when located within the noncued (*M* = .92°, *SE* = .02) object. Crucially, there was also a main effect of size, $F(1, 15) = 4.64$, $p = .048$, $\eta_p^2 = .24$, with significantly more precise target fixation on the target in the thick (*M* = .89°, *SE* = .03) than in the thin (*M* = .91°, *SE* = .02) end of the trapezoid (see Fig. 4).

The aim of Experiment 4 was to examine the link between perceptual and motor effects that influence attentional allocation. Considering the close link between attention and saccades (Corbetta et al., 1998; Kowler et al., 1995) as well as Fitts's law, we predicted a replication of our previous findings using a saccadic task. Consistent with the previous experiments, participants made more precise saccades (location of the terminal fixation) toward the target when located on the thicker end of the trapezoid, demonstrating that object size also influences overt shifts of attention. What is important to note is that there was no difference in the last fixation duration (i.e., how long participants fixated on the target before correctly deciding its identity prior to correct identification). This was calculated by subtracting the time of the onset of the last fixation from the participants' overall RT. This further precludes the alternative explanation in which the advantage on the thick end results from crowding: if this were a crowding effect, participants would have shown significantly longer RTs when discerning the identity of the target in the thin end of the trapezoid. However, the fact that the size effect was only observed on the fixation precision is evidence that object size, not object contour, is driving this effect. Note that unlike the previous three experiments, no effect of size was observed in the current experiment in RT. It should be noted that our primary measure was saccade precision, and RT differences were not expected because of the increased target presentation times and overall much longer RTs (i.e., the effect was absorbed by the eye-tracking measure).

General discussion

Real-world objects vary on many dimensions, including low-level (e.g., contrast, continuity/common region, size) as well as high-level (e.g., meaning) features. Decades of research have provided evidence that object continuity (object-based properties) robustly influences attentional allocation (Müller & Kleinschmidt, 2003; O'Craven et al., 1999; Shomstein, 2012). Although the influence of an object's physical features on attention has also been investigated (Avrahami, 1999; Behrmann et al., 1998; Marino & Scholl, 2005; Moore et al., 1998), the influence of size—one of many defining properties of any object—on attentional shifting within objects of varying sizes has not been extensively examined. In four experiments, we demonstrated that an object's width modulates shifts of attention. Experiment 1 demonstrated that target identification is faster in thicker than in thinner rectangles, regardless of whether the attentional shift was performed within or between objects. Experiment 2 utilized trapezoidal shapes to examine whether the width of the starting or landing point of the attentional shift was responsible for the size effect and demonstrated that the size of the landing point was driving the effect. Experiment 3a tested whether the size effect can be explained as interference of object contours in smaller objects (i.e., crowding) and demonstrated that the attentional benefit from object size was still evident when participants performed a target-detection task. Experiment 3b provided further evidence against the crowding explanation, showing that when object boundaries were removed (eliminating crowding during search), the attentional benefit from object width still remained. Last, Experiment 4 examined whether an object's size influences not only covert attentional shifts but overt attentional shifts as well. This last experiment provided evidence that the size of an object also influences oculomotor behavior, such that participants executed more precise saccades towards the target when it appeared within the thicker than thinner end of the trapezoid.

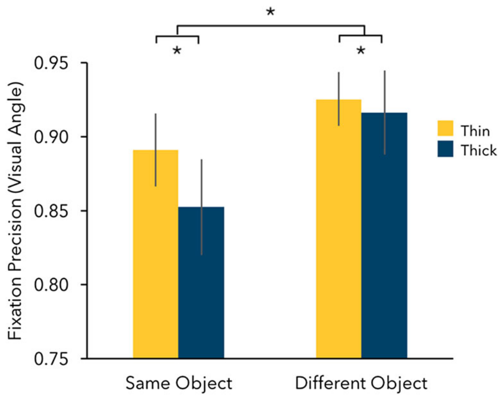

Fig. 4 Mean fixation precision for Experiment 4

These findings are compatible with accumulating evidence showing that, in the context of the two rectangle paradigm, nonspatial object properties influence attentional selection (Freeman, Macaluso, Rees, & Driver, 2014; Hollingworth, Maxcey-Richard, & Vecera, 2012; Watson & Kramer, 1999). For example, Shomstein and Behrmann (2008) demonstrated that when two otherwise identical objects differ in color, performance is better than when the two objects share color. Namely, here we demonstrate that size of objects influences object-based attentional allocation. One interesting aspect to consider is the question of why size influences attentional shifts. One possible explanation could be crowding (Strasburger et al., 1991), such that attentional shifts to targets located in more narrow objects reflect slower processing because boundaries of objects are closer to the target thus interfering with its segmentation and processing. Another possible, and perhaps more plausible explanation, has to do with the relationship between attentional shifts and motor movements.

Considering crowding as a possible explanation, careful examination of our results in fact argues against this alternative explanation. While we do observe slower RTs for targets that appeared in either thin objects (Experiment 1) or in thin object ends (Experiment 2), where object boundaries could potentially interfere with target processing, we have conducted several follow-up control experiments that provide evidence again this possible interpretation. First, the attentional benefit from object size was still present in Experiment 3a, when participants performed a target-detection task, in which crowding does not have an influence (He et al., 1997; Livne & Sagi, 2007; Pelli et al., 2004). Even more striking, perhaps, is that the effect of size was also present in Experiment 3b, when object boundaries were completely removed prior to the appearance of the search array so as to reduce any possible interference from the object boundaries when target discrimination was performed. Removal of object boundaries should have greatly reduced any contribution of edges onto RTs (Whitney & Levi, 2011). Lastly, in Experiment 4, while participants made more precise saccades to the target in the thick than in the thin condition, there was no significant difference in the duration of the last fixation. If object boundaries were interfering with task performance, we would have expected to see longer fixation duration in the thin than in the thick condition. Taken together, the results from our experiments provide strong evidence that the effect of object size on attentional deployment and target processing is not an artifact of crowding.

Given that we have excluded crowding as the source of the size effects in the experiments, we now turn to consider the link between attention and the motor system. While largely overlooked in the attention literature, the effect of an object's size has been the focus of psychophysical studies of motor movement. Fitts's law predicts that the distance between two target objects as well as the size of the objects (i.e., width) constrain motor movement (Fitts, 1954). Although this psychophysical principle is mostly used to model pointing behavior, research has provided evidence that this rule may also apply in various conditions such as in the absence of actual movements (Decety & Jeannerod, 1995) and in saccadic movements (Wu et al., 2010). The results from the current experiment demonstrate that when the distance between possible target locations was kept constant, participants were faster at overtly shifting attention toward thicker objects and executed more precise saccades (motor plans) toward the target locations. This relationship, thus, points to a possible carryover effect from motor control to attentional control.

Within the context of linking Fitts's law to attentional control, one might focus on an interesting relationship between errors and speed in motor movements as a function of object size. Fitts's law (1954) predicts a speed–accuracy trade-off movement between objects such that participants are faster but can afford to be less accurate when moving between thicker objects. While such speed–accuracy trade-offs are expected for limb movements, they are unwelcomed in perceptual experiments. First, speed–accuracy trade-offs render perceptual effects difficult to interpret. Second, these speed–accuracy trade-offs are not expected for covert shifts of attention because participants are specifically instructed to keep their eyes fixated (Prinzmetal, McCool, & Park, 2005). In the current manuscript, participants showed no difference in accuracy across all conditions that involved an attentional shift, mainly because the accuracy being measured was not how accurately a shift was executed, but rather how accurate participants were in identifying the target after a successful shift. After attention was reallocated to the end of an object, the target was processed and then identified. Therefore, we did not expect to see the speed–accuracy trade-offs traditionally associated with Fitts's law. In fact, the presence of any speed–accuracy trade-offs in our studies would have made the interpretation of our perceptual effects difficult (i.e., participants could simply have been sacrificing accuracy for faster RTs). In summary, when examining the RT results for the invalidly cued trials, attentional shifts elicited faster RTs toward thick than thin rectangles, providing evidence that the size of an object affects shifting of attention and implicating Fitts's law as a possible mechanism driving effects of size on attentional allocation.

While the effect of size on attentional shifts has not been investigated in depth to date, previous research has demonstrated that the perceived length of an object can modulate attentional shifts. Using a variant of the Ponzo illusion, Robertson and Kim (1999) demonstrated that even though the physical properties of two objects were identical, attentional shifts took significantly longer within an object that was perceived to be longer. In a set of follow-up experiments not included in this manuscript, we attempted to investigate whether the perceived size of an object (as manipulated through width) can facilitate object-based attentional shifts, utilizing a modified version of the Shepard's table illusion. This illusion is an example of size-constancy expansion, where the receding edges of one of the tables seem as if it is stretched into depth, creating the illusion that it is longer and thinner than the other table (i.e., the shapes are perceived to be of different widths), even though they are physically identical (Shepard, 1990). To fit the classic object-based attention paradigm, the vertical table was rotated until parallel with the horizontal table. However, these experiments were unsuccessful in eliciting the size effect observed in experiments reported here, either pointing to our failure to design an effective illusion capable of eliciting size effects or suggesting that object size modulates attention rather than perception.

In summary, based on the findings of the reported experiments, we suggest that the deployment of object-based attention is influenced by object size. This phenomenon mirrors the psychophysical principle that object size modulates physical movement. This principle also holds for oculomotor movements, thereby suggesting that Fitts's law may also apply to both covert and overt object-based attentional shifts. Current theories of object-based attention, such as the sensory enhancement theory (Chen & Cave, 2006, 2008; Ho, 2011), and attentional prioritization theory (Shomstein, 2012), are all based on objects of identical shapes and sizes. The current findings, however, suggest that any theory of object-based attention should incorporate an explanation of the influence of an object's size on spatial attention—faster attentional shifts between or within thick objects or toward the thicker object ends. These results add to the growing evidence that multiple aspects of object properties contribute to attentional allocation. In other words, attentional guidance to objects is constrained on the basis of multiple bottom-up object properties.

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