Looming motion primes the visuomotor system

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Abstract

A wealth of evidence now shows that human and animal observers display greater sensitivity to objects that move toward them than to objects that remain static or move away. Increased sensitivity in humans is often evidenced by reaction times that increase in rank order from looming, to receding, to static targets. However, it is not clear whether the processing advantage enjoyed by looming motion is mediated by the attention system or the motor system. The present study investigated this by first examining whether sensitivity is to looming motion *per se*, or to certain monocular or binocular cues that constitute stereoscopic motion in depth. None of the cues accounted for the looming advantage. A perceptual measure was then used to examine performance with minimal involvement of the motor system. Results showed that looming and receding motion were equivalent in attracting attention, suggesting that the looming advantage is indeed mediated by the motor system. These findings suggest that while motion itself is sufficient for attentional capture, motion direction can prime motor responses.

General Introduction

The ability to rapidly detect and react to an approaching object is essential to survival. For nonhuman animals, a looming retinal pattern might be indicative of an advancing predator whilst for humans it might represent an oncoming car. An organism’s visual system therefore faces a considerable challenge not only in rapidly detecting looming visual patterns, but also in distinguishing them from perceptually similar visual events that do not indicate threat. These include the optical flow patterns produced by stationary objects as an organism moves through the environment, or the retinal patterns produced by objects that move in a multitude of different directions. In the present study, we use the term *looming* to refer to the simulated movement of stimuli toward the observer's viewpoint such that they appear on a collision course.

One early investigation of visual sensitivity to looming motion was by Schiff, Caviness, and Gibson (1962; Schiff, 1965). In their study, adult and infant rhesus monkeys observed circular shadows on a screen that either expanded or contracted, thereby mimicking the retinal size changes generated by objects that respectively loom or recede. The observation of these silhouettes led to markedly contrasting behaviours. Whereas the monkeys continued to look at the contracting stimulus with apparent interest, the expanding stimulus elicited alarm calls and evasive responses such as ducking. Later studies in which recordings were taken directly from the visual cortices of rhesus monkeys revealed neurons that selectively responded to motion toward or away from the animal (Zeki, 1974a,b). The medial superior temporal cortex of macaques also contains cells that are sensitive to motion direction, many more of which respond to looming than to receding motion (Tanaka & Saito, 1989). Indeed, cells that are selectively tuned to looming motion are phylogenetically diverse, having also been found in the visual systems of insects (Hatsopoulos, Gabbiani, & Laurent, 1995; Peron & Gabbiani, 2009; Rind & Simmons, 1997), reptiles (Ewert, 1971), and birds (Sun & Frost, 1998).

Unsurprisingly, studies have also examined whether human observers are sensitive to looming motion. For instance, Takeuchi (1997) showed better detection for expanding targets among contracting objects than for the inverse. Similarly, Cole and Liversedge (2006) found that expanding objects were less susceptible to change blindness than were contracting objects. Furthermore, Lin, Franconeri, and Enns (2008) found that participants identified objects more rapidly when they moved on a collision path than on a near-miss trajectory. An analogous finding has been reported in 4-5-month-old infants, in which collision-bound objects elicited a larger number of blink responses than did their near-miss counterparts (Schmuckler, Collimore, & Dannemiller, 2007). Thus the manner in which even perceptually naive infants respond suggests that sensitivity to looming motion may be hardwired, although recent evidence has suggested that the neural networks for registering impending collision become fully developed only by 10-11 months of age (van der Weel & van der Meer, 2009).

Although the evidence for neural specialization to looming motion is compelling, the issue of whether such motion can automatically attract attention has generated considerable debate. Indeed, much of the evidence cited above concerns responses to looming motion that is already attended. Thus the issue at hand is whether a looming object is capable of summoning attention that initially may lie elsewhere in the visual scene. Here the evidence is mixed. Franconeri and Simons (2003) assessed the question using the *singleton paradigm* (e.g., Cole, Kuhn, Heywood, & Kentridge, 2009; Egeth & Yantis, 1997; Yantis & Jonides, 1984; Jonides & Yantis, 1988; Gellatly, Cole, & Blurton, 1999). The paradigm involves participants searching for a target letter amongst distractor letters in arrays of varying size. One item in the array is always unique (i.e., is the ‘singleton’) in that it differs from the other items by a single attribute, e.g., color, brightness or size. Importantly, the singleton and the target are independent in the array, but on occasion will coincide. One can assess whether the singleton has successfully attracted attention by examining reaction times when the target was the unique or a non-unique item. An affirmative result is evidenced by a search slope for unique targets that is relatively independent of array size; that is, a search function that is shallower, flat, or even negative compared to that yielded by non-unique targets (Simons, 2000; Treisman, 1986; Wolfe, 1998; Yantis & Jonides, 1984).

The singleton used by Franconeri and Simons (2003) was a placeholder item that either expanded (loomed) or contracted (receded) in an array of static placeholder items. Motion took place immediately prior to the items transforming into a target search array. The resulting search slopes indicated that looming objects attracted attention whereas receding objects did not. This conclusion received further support from von Mühlenen and Lleras (2007) using a probe detection paradigm. Their experiments used arrays of randomly moving dot patterns. At some point in each trial, the dots in one half of the array gradually transformed from random into looming or receding motion patterns (simulated, respectively, by the dots emanating from or converging toward a central vanishing point). Dots in the other array half maintained their random motion. Attentional preference for either motion pattern was probed on each trial with a target that appeared in one of the array halves. Results showed that in comparison with target detection in the random arrays, performance was improved in the looming but not the receding arrays.

In contrast to those findings, Abrams and Christ (2005a) found that receding objects are capable of attracting attention. They used the same singleton paradigm as Franconeri and Simons (2003), but generated receding objects stereoscopically, combining size changes with binocular disparity to create apparent motion in three-dimensional depth. Under these conditions, receding targets did attract attention, suggesting that attentional capture is not contingent upon motion direction. Rather, they argued, motion onset is the stimulus for capture (Abrams & Christ, 2003, 2005a,b). This interpretation clearly challenges the conclusions of Franconeri and Simons (2003), and von Mühlenen and Lleras (2007).

One of the inherent difficulties in simulating motion in depth in a laboratory setting is determining which of the many cues used by the human visual system to compute depth provides the most compelling percept. Some of these cues result from binocularity such as ocular vergence angle (Collewijn & Erkelens, 1990; Mon-Williams, Tresilian, & Roberts, 2000; Richard & Miller, 1969; Ritter, 1977; Viguier, Clement, & Trotter, 2001) and retinal disparity (Bishop, 1989; Mayhew & Longuet-Higgins, 1982), whilst monocular cues such as retinal blurring (Mather, 1997; O'Shea, Govan, & Sekuler, 1997), ocular accommodation (Mon-Williams & Tresilian, 1999, 2000), as well as the surface texture, contrast and shading of fixated objects are also influential (Gonzalez & Perez, 1998; Johnston, 1991; Johnston, Cumming, & Parker, 1993; O'Shea, Blackburn, & Ono, 1994).

Furthermore, observers are able to extract information about an object's movement in depth by its optical size and rate of size change (DeLucia & Novak, 1997; Hosking & Crassini, 2011). One concern with the studies investigating the attentional effects of looming and receding motion is that a variety of techniques were used, such as size changes to two-dimensional figures (Franconeri & Simons, 2003), optical flow patterns (von Mühlenen & Lleras, 2007), and binocular disparity (Abrams & Christ, 2005a). Our examination of capture by motion in depth (Skarratt, Cole, & Gellatly, 2009) began by addressing Abrams and Christ's (2005a) omission of looming items from their experiment. While their interest lay only in whether receding objects can attract attention, we sought to establish whether the two motion types differ in the extent of their prioritization. We therefore adopted their technique of using stereoscopic motion in depth. Our results were very clear in showing that, compared to static items, looming and receding objects were equivalent in attracting attention. This was evidenced by slope functions that were shallower than for static targets, yet parallel with one another. However, overall reaction times (RTs) to looming targets were shorter, an intercept effect we refer to as the *looming advantage*.

Given the tradition of inferring attentional processing differences on the basis of search slopes rather than intercept effects (see Simons, 2000, for an overview), the data seemed to indicate that the looming advantage must occur either pre- or post-attention, but not during attentional selection. Hence the overall reaction time advantage has to reflect processes operating either side of selection. We speculated that this likely represented more efficient post-attentional processing, such as during response preparation and/or execution. In other words, whereas attention may be attracted to the onset of motion or to motion per se (e.g. Abrams & Christ, 2003; 2005a; 2005b; 2006; Franconeri & Simons, 2003; 2005), perhaps motion *direction* differentially primes motor responses. Indeed, such a proposition is intuitive in the context of self-locomotion or processing threat: It is more advantageous to evade a looming object than it is to identify it.

The present experiments tested whether the looming advantage is indeed mediated by the motor system. We began by replicating the basic effect (Experiment 1), whilst indexing it across a greater number of array sizes than did Skarratt et al. (2009). Thereafter, the purpose of Experiments 2–4 was to examine alternative explanations for the looming advantage. One disadvantage of using binocular disparity and size changes to simulate motion in depth is that motion singletons are associated with other singleton features, any of which might account for the RT intercept effect that characterizes the looming advantage. For instance, the items began each trial in different depth planes before moving into alignment with the static items. Experiment 2 therefore examined the effect of the starting depth of objects. A second constituent feature of motion through stereoscopic depth is that objects are seen to move horizontally under monocular viewing conditions. Hence, Experiment 3 asked whether the lateral direction of motion could account for the looming advantage. Experiment 4 examined whether our modification to the original singleton paradigm – employing two competing singletons rather than just one – might give rise to the intercept effect. That is, the looming advantage might simply reflect how the visual system organizes equally salient items as they compete for attention. This was investigated by replacing the looming and receding items with two different singletons. In Experiments 2 – 4, therefore, our reasoning was to determine whether the intercept effect could be explained by the associated features of stereoscopic motion, or the singleton paradigm itself. This in turn would indicate whether the looming advantage arises from looming motion itself, or from one or more of its constituent features. To preview our findings, results showed that none of these features can explain the looming advantage. Finally, Experiment 5 offered a direct test of the motor hypothesis by using a perceptual measure of performance, thereby minimising the involvement of the motor system. We reasoned that if the looming advantage was absent using this measure, it would provide strong evidence that primacy for looming motion is motoric rather than perceptual in nature. Our results suggest that is indeed the case.

Experiment 1

The starting point was to replicate the looming advantage reported by Skarratt et al. (2009; Experiment 2). In their experiment, participants viewed stereoscopic arrays containing three or six figure-eight placeholder shapes. One of the placeholders was designated as a “looming” item. This appeared, due to its binocular disparity and a small decrease in retinal size, to be positioned in a farther depth plane than the other items. Another item, the “receding” item, was positioned in the same manner so as to appear “in front” of the other items. Motion was simulated by having the two placeholders move into alignment with the other figures until zero disparity was reached (see Figure 1). This preview display then transformed into a search array and participants searched for a target letter amongst distractors.

The generality of the basic effect was explored in a modified replication involving three key changes to Skarratt et al.'s method. First, performance was examined across a greater number of array sizes. The original method of comparing arrays of three versus six items meant that the looming and receding search functions were derived from only two data points each. Hence, whether the two slopes were convergent, divergent or parallel rested on the position of any single data point of the possible four. Slight variation in the positioning of just one data point in relation to the other three would therefore be interpreted as favouring either the attentional or motor account over the other. To give a clearer impression of whether the looming advantage could manifest as a difference in intercept, slope, or both, array sizes of three, four, five or six items were used. This meant that the looming and receding search functions were each based on four data points.

A second change was incorporated to determine whether the attentional effect of looming and receding motion is one of prioritization or *capture*. That is, to assess the efficiency with which attention is directed to motion. Skarratt et al. (2009) obtained slope efficiencies of 23 ms/item for looming and 26 ms/item for receding targets. However, search that yields slopes close to 30 ms/item or above is typically viewed as inefficient (Wolfe, Palmer, & Horowitz, 2010), as efficient search often yields flat or even negative search functions. It seems surprising given the intuitive threat posed by approaching objects that they might give rise to relatively inefficient search, so this warranted further investigation. One potential explanation for this puzzle is that distracter items were randomly drawn from a pool containing the letters ‘A’, ‘E’, ‘U’, ‘P’, ‘C’, and ‘F’, while targets were composed of the letters ‘S’ or ‘H’. Thus the degree of luminance change generated by the placeholder elements as they transformed into distractors varied according to the number of offsetting segments (between 1–3). In contrast, target elements always generated consistent luminance transients by shedding just two segments. As a result, looming or receding targets were always required to compete for attention with lesser or greater luminance changes occurring elsewhere. In the present experiment, therefore, homogeneous distractors were used (i.e., either all ‘E’s or all ‘U’s) such that the targets and distractors all underwent the same change in luminance as they transformed from their placeholders. This ensured that targets and distractors differed only on the basis of their identity and motion type, and not by the strength of their associated luminance change.

The final modification permitted an empirical examination of whether the changing relevance of the singletons in this paradigm influences performance. In a typical singleton paradigm (e.g., Cole & Kuhn, 2010; Gellatly et al., 1999; Yantis & Jonides, 1984; Jonides & Yantis, 1988), the singleton and the target coincide on 1/n of trials, where n is the array size. Hence the relevance of the singleton changes as a function of array size, with the looming and receding elements more task relevant in smaller arrays than in larger arrays. The present experiment maintained the probability of the target being a looming, receding or static item at 1/3, irrespective of set size. The observation of the looming advantage in spite of these three changes would provide a clear indication of its reliability and generality.

Method

Participants. Eighteen undergraduates (12 male, aged between 20-23, all right-handed) participated in a single 1-hour session. All had normal or corrected-to-normal binocular vision, and were naïve to the purposes of the experiment.

Apparatus and stimuli. The experiment was conducted on a Pentium PC linked to an 85-Hz CRT color monitor (CTX, 18”, 800 × 600 pixels). A stereoscope restricted the view of each eye to only one half of the stimulus array, thus allowing binocular disparity to provide the primary depth cue. The trial sequence is shown in Figure 1. Each trial began with a fixation display comprising either three, four, five or six figure-eight placeholders that were positioned randomly at the vertices of a virtual hexagon. This measured 9° in diameter when viewed from 68cm. Each placeholder shape measured 2.1° × 1.1° and appeared dark grey (7.85 cd/m^2) against a black (0.04 cd/m^2) background. All display items were presented at zero disparity, with the exception of two randomly selected placeholders. In one half of the stereo image, the looming item was displaced by 0.6° to the right of its corresponding position in the other half, with the receding item displaced 0.6° to the left. We computed the distance of the items in front and behind of the screen using the following formula:

$$D = d\left(\frac{E}{I - d}\right)$$

where D is the depth position (in cm) from the fixation plane, E is the viewing distance to the fixation plane (68 cm), I is the interocular distance (6.5 cm) and d is the disparity (in cm) between the stimuli (see Appendix for the derivation of this formula). At the beginning of each trial, the looming and receding placeholders sat approximately 8.2 cm either side of the fixation plane, with the retinal sizes of these placeholders adjusted to maintain size constancy, and size consistency, with the other items. This gave an initial size of 1.8° × 0.8° for the looming placeholder and 2.5° × 1.4° for the receding placeholder. After a fixation array lasting 3000 ms, these two placeholders moved into alignment with the zero disparity placeholders to create illusory motion in depth. The motion occurred at a velocity of 54.7 cm/s and was completed in 150 ms. The array then became a search array, with each placeholder shedding two of its segments to reveal a letter. One item became a target (either an 'S' or an 'H'), while the others became distractors (either all 'E's or 'U's). Participants identified the target as quickly and as accurately as possible by pressing one of two keys on a standard keyboard. The response key mapping was reversed for half of the participants. The search array remained until a response was made or until 2500 ms had elapsed. Participants were instructed to maintain fixation throughout each trial.

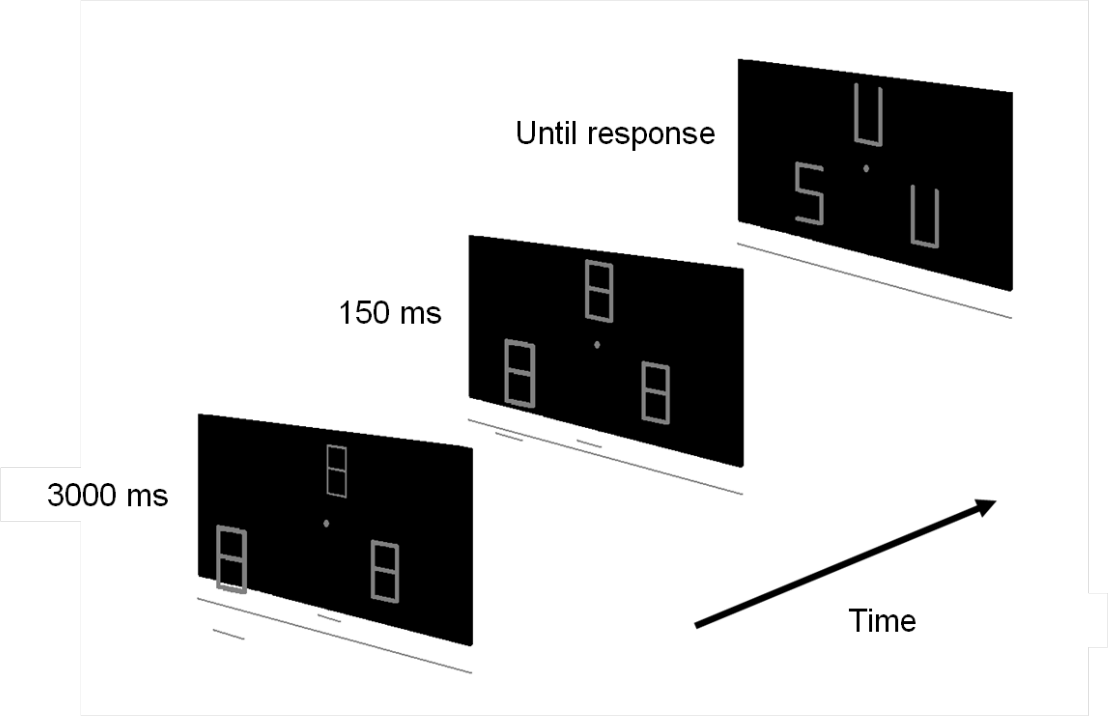

Figure 1. Sequence of trial events in Experiment 1. The figure depicts placeholders that are designated as looming, receding, or static items. The looming and receding items begin each trial, respectively, in a farther and nearer depth plane than the other item(s), and then moved into mid-plane alignment over the course of 150 ms. The placeholders then transformed into letters. See the main text for additional information.

Design and Procedure. A 4 × 3 within-participants design was employed, with array size (3, 4, 5, or 6) and target motion type (looming, receding, or static) as factors. Participants undertook a single block of 576 trials that were equally divided according to array size. Each trial contained a looming and a receding placeholder, whilst the remaining were static items. The target was equally likely to be a letter ‘S’ or ‘H’, as it was to be a looming, receding or static item irrespective of array size. Before testing, participants were given a single block of 32 practice trials, and were offered a break after every 96 trials in the experiment proper.

Results and Discussion

Data from one participant were removed due to a disproportionately high error rate (>20%). Accuracy for the remaining participants was above 95% in all conditions. Accuracy scores were submitted to a 4 × 3 within-participants ANOVA, with factors of array size (three, four, five, or six) and motion type (looming, receding, or static). Only the main effect of motion type was significant, $F(2,32) = 3.79$, $p < 0.04$, partial $\eta^2 = 0.19$, reflecting greater accuracy for looming targets ($M = 98\%$, $SD = 2.3$) than to receding targets ($M = 96\%$, $SD = 1.8$), $t(16) = 2.21$ $p < 0.05$, and to static targets ($M = 96\%$, $SD = 2.4$), $t(16) = 2.94$, $p < 0.05$. Accuracy for receding and static targets did not differ $t(16) = 1.18$, $p > 0.25$.

Statistical criteria for the looming advantage

Skarratt et al. (2009) found that overall RTs were shorter to looming targets than to receding targets. Importantly, the RT difference remains constant across array size, manifesting as a significant main effect and a non-significant interaction. This distinctive pattern allows one to stipulate *a priori* the criteria by which the looming advantage would be observed in the present Experiment 1, and all corresponding effects judged to have occurred in Experiments 2-4. These statistical criteria are twofold.

First, mean RTs for each target type (looming, receding, static) by array size are submitted to an omnibus ANOVA. A significant interaction likely indicates that both motion types attract attention relative to static targets. Second, therefore, a further two-way ANOVA focuses on RTs to looming and receding targets across array size. The looming advantage is inferred from a significant main effect of motion type, revealing shorter RTs to looming targets, and a non-significant interaction (i.e., same slopes, different intercepts). Note that the analyses are performed on mean RT data while the slope values are provided for illustrative purposes only.

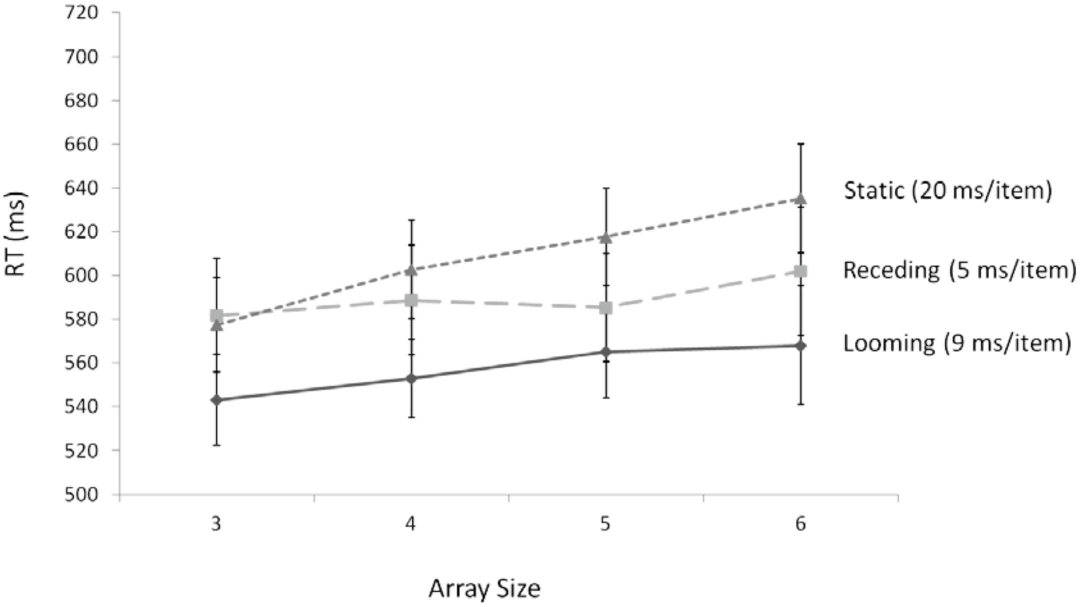

Figure 2. Mean correct RTs as a function of array size and motion type, from Experiment 1. Slopes are labelled according to target motion type, with search efficiency values given in parenthesis. Error bars indicate ±1 SEM.

All RTs lying either side of two standard deviations of each participant's condition mean were removed as outliers[1]. This accounted for 4.8% of all responses. The mean RTs from the remaining correct response trials are shown in Figure 2. As can be seen, the RT search slopes for looming, receding, and static items were 9 ms/item, 5 ms/item, and 20 ms/item, respectively; the highly efficient search promoted by the two motion types suggesting they captured attention relative to the static items. In accordance with the statistical criteria outlined above, the mean RTs were submitted to a 4 × 3 within-participants ANOVA, with array size (three, four, five, or six) and motion type (looming, receding, or static) as factors. Significant main effects were obtained for array size, $F(3,48) = 14.06$, $p < 0.001$, partial $\eta^2 = 0.47$, and motion type, $F(2,32) = 32.12$, $p < 0.001$, partial $\eta^2 = 0.67$. The interaction also was significant, $F(6,96) = 2.49$, $p = 0.028$, partial $\eta^2 = 0.16$.

To examine whether the apparent looming advantage seen in Figure 2 was significant, a 4 × 2 ANOVA examined RTs to looming and receding targets for each array size. Of lesser importance, the main effect of array size was significant, $F(3,48) = 3.36$, $p = 0.026$, partial $\eta^2 = 0.17$. Of greater interest, however, was the main effect of motion type, $F(1,16) = 16.53$, $p < 0.001$, partial $\eta^2 = 0.51$, confirming that looming targets attracted faster responses. This effect, combined with a non-significant interaction, $F(3,48) < 1$, partial $\eta^2 = 0.038$, confirm the basic same-slope-different-intercept effect that characterizes the looming advantage.

In spite of the three significant changes to the original method, the present results clearly replicate those of Skarratt et al. (2009). Taken together, the two studies demonstrate a high degree of consistency, showing that the looming advantage is resistant to the number and type of distractors competing for attention, and the probability of associated targets. The two sets of results indicate that looming and receding objects are prioritized in more visually dynamic arrays, yet *capture* attention when competing distractor items undergo the same change in luminance. However, those observations concern how moving targets are processed in relation to static items. Their slopes in comparison with one another suggest once again that motion direction is not encoded during attentional selection. Our thesis is that once selected, looming motion primes the motor system.

Experiments 2–4

The next three experiments were motivated by the same purpose: to examine whether the looming advantage could be explained by any of the constituent features underlying stereoscopic motion in depth, or by our modification of the singleton paradigm. The decomposition of stimuli into their component parts can offer important insights into whether the visual system responds to featural aspects of their makeup or their holistic representation. One example is Cole, Kentridge and Heywood's (2004) examination of the new object hypothesis. Previous research had indicated that the visual system is highly sensitive to abrupt onset stimuli, such that new objects are capable of rapidly attracting attention (e.g., Yantis & Jonides, 1984). However the abrupt appearance of a new object can be signalled by several associated visual events, such as transient changes in luminance, colour, and contour. Using a one-shot change blindness task, Cole et al. compared detectability for object onsets with that for existing objects undergoing equivalent changes to their composite features. In all cases, however, changes to those features were more likely detected when they were associated with new objects than with existing objects. In a similar vein, Tanaka and Farah (1993) showed that individual components of a face – the eyes, nose and mouth –

were more easily recognized when presented in the context of an intact face than a scrambled face. This method of deconstructing stimuli into their constituent features therefore suggests that for certain behaviourally relevant stimuli, their configural representation is more accessible than that of their component parts. Hence in the present Experiments 2 and 3, there is the distinct possibility that none of the constituent features of stereoscopic looming motion can explain the looming advantage. In that event, the data would suggest a stronger visuomotor response to looming motion *per se* than to any single underlying monocular or binocular features of that motion.

In Experiment 1, the stereoscopic rendering of motion required that the placeholders designated as looming, receding, or static had to begin each trial, respectively, in a far, near, or middle depth plane. This was to ensure that they completed their motion paths in the same (middle) depth plane in time for the search array, thus ensuring equal perceptibility of the target and distractor items. Consequently, however, motion direction was therefore confounded with initial depth, such that the motion singletons were also depth singletons. Franconeri and Simons (2005) have argued against simulating looming and receding motion in stereo depth, pointing out that observers may preferentially select (in this case) the farthest item and track it attentively as it looms forward. Although it is possible such a strategy could account for the looming advantage, data from the only two studies we know to touch upon this issue suggest it is unlikely. Neither study directly sought to investigate attention in near versus far depth planes per se, but Theeuwes, Atchley, and Kramer (1998), and O’Toole and Walker (1997), report tasks in which participants searched for targets across two depth planes. Theeuwes et al. found no difference in RT or accuracy rates as a function of depth, whilst O'Toole and Walker found that targets were detected more efficiently when they appeared in front of their accompanying distractors than when they appeared behind. Hence, one might not expect the initial depth position to make a difference or, if so, to favour the receding item for being closer than the others. Nevertheless, Experiment 2 offered a direct test of this possibility by partially replicating Experiment 1, but with the motion sequence removed. The trials began with two placeholders standing either side of the mid-plane item(s), after which the array disappeared for 150 ms. The stimuli then reappeared as a search array with all items occupying the middle depth plane.

In the same vein, Experiment 3 addressed the potential effect of horizontal motion on the looming advantage. The arrays in Experiment 1 were constructed such that stereoscopic motion required one of the eyes to view the looming stimulus moving leftward and the receding stimulus moving rightward. There is evidence demonstrating that spatial attention shows a left-to-right bias (e.g., Spalek & Hammad, 2005), so it might be argued that the looming object distinguishes itself by contradirectional motion. To investigate this, Experiment 1 was partially repeated, but this time with the placeholders confined to horizontal movements. Finally, the purpose of Experiment 4 was to examine the potential effect of two salient items competing for attention within the same arrays. This modification to the singleton paradigm is novel[2], and the resulting slope and intercept pattern may simply reflect how in such a situation the visual system organizes equally salient information that competes for attention. This possibility was investigated by replacing the looming and receding singletons with two different singletons that were salient along other featural dimensions. One item was a color singleton and the other was a size singleton. The shared aim of Experiments 2-4 was to establish whether the slope and intercept pattern that characterizes the looming advantage could be reproduced with any of the manipulations described above. Indeed, a successful reproduction would indicate that the looming advantage arises from one or more of the constituent features of stereoscopic looming motion, or from our modification of the paradigm itself. In contrast, any other pattern would indicate that the RT benefit derives from mechanisms sensitive to looming motion itself.

General Method

Participants. Each experiment comprised a different set of 15 participants, none of whom had served previously.

Apparatus and stimuli. The stimuli and trial sequences in Experiments 2 – 4 were based on those in Experiment 1 and are illustrated in Figure 3. The changes were as follows. In Experiment 2, the entire motion sequence was replaced with a blank frame that contained only a fixation point (Figure 3A). In Experiment 3, the fixation array comprised one placeholder that was shifted leftward and one rightward by 0.6° at the start of each trial. These placeholders then moved into position at the vertices of the imaginary hexagon over the course of 150 ms (Figure 3B). The initial placeholder displacement and subsequent motion sequence were identical to those viewed by one of the eyes in Experiment 1. In Experiment

4, the motion singletons were replaced by one isoluminant red color singleton (7.66 cd/m^2) and one size singleton (3.3° × 1.9°; Figure 3C). Although only Experiment 2 required simulation of three-dimensional depth, all stimuli were generated and viewed stereoscopically, albeit with zero disparity in Experiments 3 and 4.

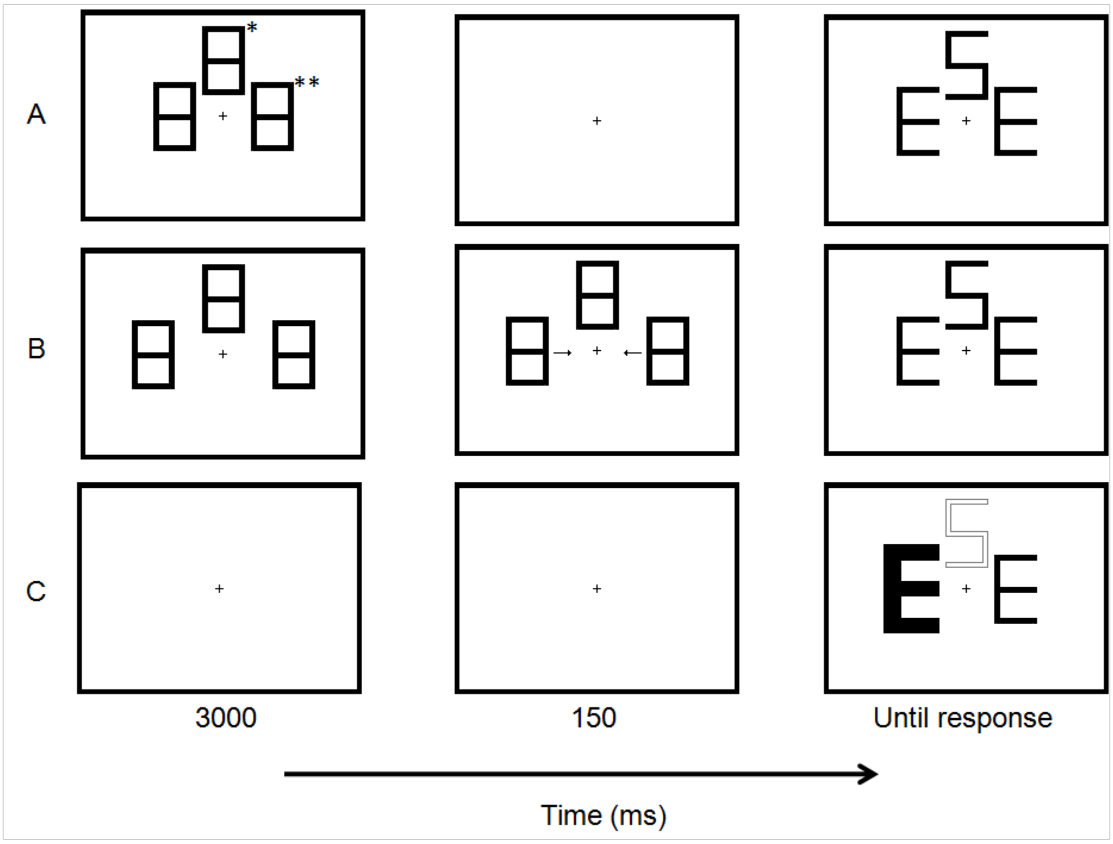

Figure 3. Sequence of trial events in Experiment 2 (panel A), Experiment 3 (panel B), and Experiment 4 (panel C). Stimuli are not depicted to scale, and are shown in reverse contrast to their actual appearance. The arrows in panel B illustrate the motion path and were not present in the actual stimulus array, while the outline figure in panel C depicts an isoluminant colour singleton present on each trial. See the main text for additional information. *far depth plane; **near depth plane.

Design and Procedure. The experiments were all 2 × 3 within-participant designs, manipulating array size (3, 6) and singleton type (Experiment 2: near, far, middepth plane; Experiment 3: leftward motion, rightward motion, static; Experiment 4: color, size, uniform grey). Each experiment comprised a practice block of 24 trials, followed in the experiment proper by 216 trials, divided equally according to array size and singleton type.

Results

Outliers were removed as in Experiment 1. This resulted in the omission of 4.6% of responses in Experiment 2, 5.5% in Experiment 3, and 5.2% in Experiment 4. Accuracy and RT data from the correct trials were submitted to 2 × 3 within-participant ANOVAs, with array size and singleton type as factors.

Experiment 2: Starting depth. Accuracy was above 96% in all conditions and did not differ according to array size or the starting depth of targets (all ps > 0.13). As can be inferred from Figure 4 (left panel), the only significant main effect on correct-response RTs was of array size, $F(1, 14) = 54.95$, $p < 0.001$, partial $\eta^2 = 0.8$. All other ps > 0.2. Critically, as the interaction was not significant, $F(2, 28) = 1.63$, $p = 0.22$, partial $\eta^2 = 0.1$, no further analysis was conducted on the near and far target RTs. The results are clear in showing that the initial depth of placeholders has no effect on search efficiency.

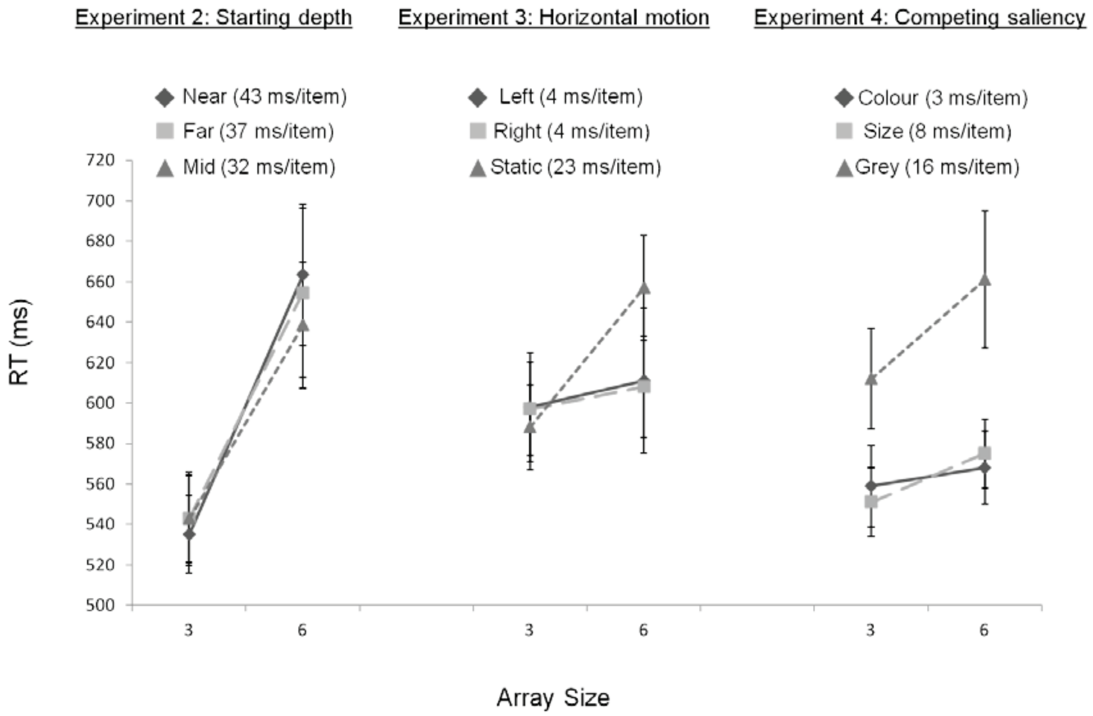

Figure 4. Mean correct RTs as a function of array size and target type according to their starting depth (Experiment 2), lateral motion direction (Experiment 3), or color or size (Experiment 4). Slope efficiencies are shown in parenthesis. Error bars indicate ±1 SEM.

Experiment 3: Horizontal motion. Accuracy was above 95% in all conditions and none of the effects reached significance (all ps > 0.15). For correct-response RTs, the only significant main effect was for array size, $F(1, 14) = 15.88$, $p = 0.001$, partial $\eta^2 = 0.53$. The interaction was also significant, $F(2, 28) = 6.93$, $p = 0.004$, partial $\eta^2 = 0.33$. In accordance with the statistical criteria set out for Experiment 1, planned comparisons focused on the two motion types as a function of array size, omitting static target RTs. Importantly, there was no difference between leftward and rightward targets in terms of overall RTs, $F(1, 14) = < 1$, partial $\eta^2 = 0.002$, nor did they interact, $F(1, 14) = < 1$, partial $\eta^2 = 0.002$. As can be seen in the centre panel of Figure 4, then, while lateral motion successfully attracts attention from the static items, the direction of motion is not influential.

Experiment 4: Competing saliency. Accuracy was above 94% in all conditions. The only effect to reach significance was of array size, $F(1, 14) = 5.73$, $p = 0.03$, partial $\eta^2 = 0.28$, reflecting greater accuracy in arrays of six (M = 98%, SD = 0.9) than of three (M = 96%, SD = 0.7). All other *p*s > 0.07. The array size effect was also significant in terms of correct-response RTs, $F(1, 14) = 18.15$, $p = 0.001$, partial $\eta^2 = 0.57$, as was the main effect of singleton type, $F(2, 28) = 17.02$, $p < 0.001$, partial $\eta^2 = 0.55$. In terms of overall RTs and slope differences, inspection of Figure 4 (right panel) suggests both singleton types captured attention relative to the uniform grey items. The interaction reached significance, $F(2, 28) = 3.45$, $p = 0.046$, partial $\eta^2 = 0.2$. As before, this was followed up by analysing RTs to both singleton types as a function of array size. As is suggested by Figure 4 (right panel) the two singleton types conferred almost identical RTs, $F(1, 14) < 1$, partial $\eta^2 = 0.001$, and did not interact with array size, $F(1, 14) = 1.91$, $p = 0.19$, partial $\eta^2 = 0.12$. Similar to the results of Experiment 3, then, both singleton types captured attention but their effects in relation to one another were indistinguishable.

Taken together, the results of Experiments 2–4 are unequivocal in showing that none of the visual features underlying stereoscopic motion in depth can account for the looming advantage observed in Experiment 1 and in the studies of Skarratt et al. (2009). Although horizontal motion (Experiment 3), color and size singletons (Experiment 4) did capture attention, none of these stimulus features displayed the characteristic intercept effect that distinguishes processing of looming motion from receding motion. Indeed, the same-slope-same-intercept effects shown for these singletons are precisely what one would expect from features that receive parity throughout the information processing system. Having therefore ruled out these confounds as potential explanations for the looming advantage, we propose that the intercept effect is indicative of post-attentional mechanisms that selectively respond to motion direction. We posit that these processes are not perceptual in nature; rather, they are motor-based and involved in response programming and/or execution. This idea was tested in Experiment 5.

Experiment 5

If the looming advantage is indeed mediated by motor processes, it is hardly surprising that its presence should be revealed with RT, to which the motor system makes a significant contribution. In contrast, the advantage should be absent whenever a perceptual measure is used. That was the rationale for Experiment 5. To that end, we used a temporal order judgement (TOJ) task in which participants identified which of two targets appeared first. The principle underlying TOJs, that of *prior entry*, has long been known to experimental psychologists, having been described by James (1898) and Tichener (1908). Both noted that attended stimuli are perceived earlier than unattended stimuli. The strength of the phenomenon is such that an unattended stimulus must precede an attended stimulus by approximately 40 ms before the two are judged as simultaneous (Stelmach & Herdman, 1991). Thus, the attentional preference for one stimulus over the other can be assessed by which of two asynchronous stimuli is correctly judged to have occurred first.

This principle was exploited in Experiment 5 by having participants determine the arrival order of two target letters. The first target (T1) was associated with a looming, receding or static placeholder with equal probability, whilst the second target (T2) was equally likely to be one of the remaining two placeholder types. As attention is attracted by motion *per se*, it was expected that accuracy for identifying T1 would be elevated when T1 was moving rather than static. However the more important question concerned performance when T1 was either a looming or a receding item: If the looming advantage reflects enhanced perceptual processing, accuracy should be greatest for looming, receding, and then static T1s, in that order. Conversely, if looming motion primes only the motor system, looming and receding T1s should yield similar accuracy scores.

Method

Participants. A different set of 22 undergraduate students took part in exchange for course credit.

Apparatus and stimuli. These were as described for Experiment 1, with three exceptions. First, given that the looming advantage was evident in the three-item arrays in Experiment 1, only three items were presented here (one looming, one receding, and one static element). Second, two targets – S and H – were used. After the motion sequence was completed, one of the placeholders transformed into T1, followed 80 ms later by T2. The third item in the array remained as a figure-eight placeholder. Third, participants were asked to identify which of the two targets transformed first, with a strong emphasis placed on the accuracy rather than the speed of response.

Design and Procedure. Twenty-four practice trials were followed by a block of 144 experimental trials, with a break occurring halfway. These trials were divided equally according to whether T1 was associated with the looming, receding or static placeholder. Thus, of the 48 trials in which T1 was a looming item, 24 contained T2 as the receding item and 24 as the static item. The corresponding permutations were implemented when T1 was the receding item and when it was the static item.

Results

Mean percentage accuracy scores are shown in Figure 5 (panel A). These were submitted to a one-way ANOVA, which confirmed differences in TOJ accuracy for looming, receding and static T1s, $F(2, 42) = 51.72$, $p < 0.001$, partial $\eta^2 = 0.71$. As is evident in the figure, accuracy was significantly improved when T1 was a moving item compared to when it remained static (looming versus static, $t(21) = 7.55$, $p < 0.001$; receding versus static, $t(21) = 9.25$, $p < 0.001$). Accuracy did not differ, however, when T1 was either a looming or receding item, $t(21) = 1.47$, $p > 0.15$. Hence participants were more accurate in making TOJs when T1 was a moving item, yet the direction of motion did not affect performance.

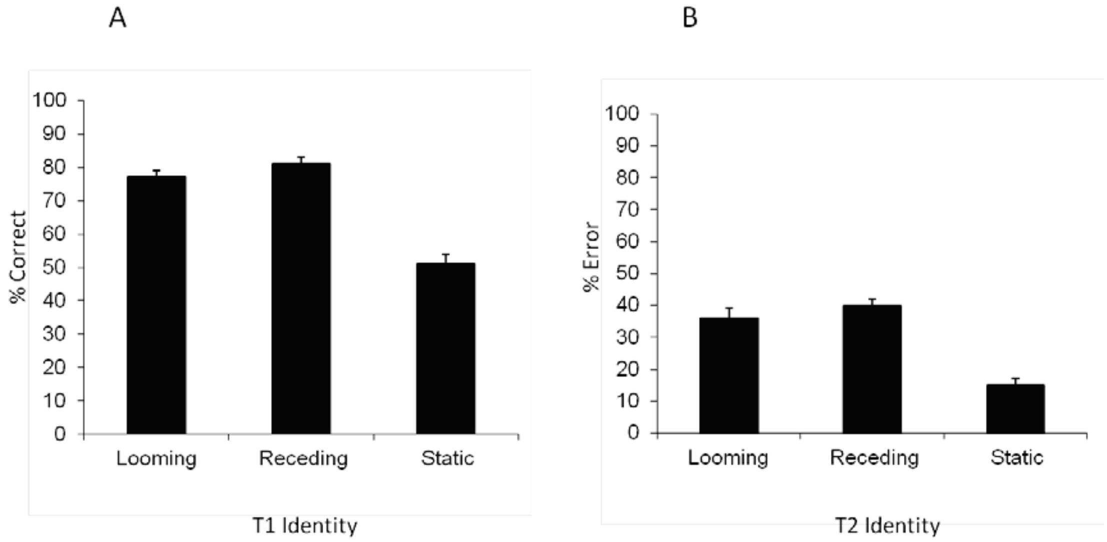

Figure 5. Panel A: Mean TOJ accuracy (%) when T1 coincided with the looming, receding, or static item, from Experiment 5. Panel B: Mean TOJ errors (%) when T2 coincided with the looming, receding, or static item, from Experiment 5. Error bars indicate 1 SEM.

This observation was also reflected in the distribution of TOJ errors. An error was defined as a response indicating that T2 had appeared first. These data are displayed in panel B of Figure 5, and show an increase in errors when T2 was a moving item. A one-way ANOVA indicated significant variation across the three conditions, $F(2, 42) = 34.65$, $p < 0.001$, partial $\eta^2 = 0.62$, while simple effects analyses confirmed that errors increased when T2 was a looming rather than a static item, $t(21) = 6.76$, $p < 0.001$, and when it was a receding than a static item, $t(21) = 7.9$, $p < 0.001$. As with the corresponding effect on T1, however, the distribution of errors did not differ when T2 was a looming or a receding item, $t(21) = 1.07$, $p = 0.3$. Thus the accuracy and error data are highly consistent: attention is attracted to moving rather than static objects, but motion direction does not influence prior entry. We therefore conclude that the RT advantage for looming motion results from motor priming.

General Discussion

A wealth of evidence now indicates that humans are highly sensitive to looming motion (e.g., Lin et al., 2008; Takeuchi, 1997; Schmuckler et al., 2007; van der Weel & van der Meer, 2009). Much of this evidence concerns looming motion that is already attended; the wider issue of whether attention is preferentially attracted to looming motion is more contentious (Abrams & Christ, 2003, 2005a, b, 2006; Franconeri & Simons 2003, 2005; Skarratt et al., 2009; von Mühlenen & Lleras, 2007). The central focus of the present study was to examine a hypothesis proposed by Skarratt et al. (2009), who found that visual search efficiency was similar for looming and receding targets, but that looming targets elicited overall shorter RTs. Their suggestion was that while looming and receding motion are equivalent in their ability to capture attention, looming motion primes the motor system such that a response can be more readily prepared.

We examined visuomotor sensitivity to looming motion across five experiments. Experiment 1 sought to replicate the basic looming advantage whilst also assessing the generality of the effect. To this end, performance was examined when the task-relevance of looming objects remained constant across array sizes of three, four, five and six items, and when target and distractor stimuli generated identical sensory transients. In spite of those significant changes to Skarratt et al.'s original method, the looming advantage was still observed. Experiments 2 – 4 served a common purpose. That was to establish whether the intercept difference that characterizes the looming advantage can be explained by the underlying features of stereoscopic motion in depth, or reflects the way in which the visual system organizes competing items of varying salience. Thus, Experiment 2 examined the effect of the starting depth of items, rather than their motion through depth. Experiment 3 examined the effect of horizontal motion, a monocular cue required to generate the binocular impression of motion through depth; and Experiment 4 presented color and size singletons in place of the looming and receding items. Results showed that none of these potential confounds could account for the looming advantage. Performance was identical irrespective of the starting depth of targets. Although attention was captured by horizontal motion, and by color and by size singletons, their equivalence in attracting attention was marked by overlapping search slopes. In none of those cases did we see the distinctive intercept difference that characterizes the looming advantage. Thus it appears that enhanced processing is afforded to looming motion itself rather than to any of its composite features.

Having ruled out these alternative explanations for the looming advantage, Experiment 5 tested the motor hypothesis using a perceptual measure. We reasoned that if the looming advantage does indeed result from motor priming, it ought to be absent when measuring accuracy. A TOJ task was therefore used in which participants judged which of two asynchronous targets appeared first, with T1 equally likely to be associated with looming, receding or static placeholders. If the looming advantage reflects an enhancement of perceptual attention, we expected greater accuracy for looming T1s. As it was, T1 attracted more correct judgments only when it was a moving rather than a static item, with no difference in accuracy between looming and receding T1s. Although one could question the interpretation of this null effect, we can reasonably be assured the experiment had the required sensitivity to detect differences between the two motion types should they exist. Indeed, the experiment did detect prior entry differences between moving and non-moving stimuli, and to that end the results were entirely consistent with the slope data from Experiment 1. Both experiments point toward motion itself being the stimulus for attentional capture, and not motion direction. Thus the presence of the looming advantage when measuring RT, followed by its absence when measuring only perception, provides a strong indication that its basis lies in the motor system.

As well as explaining the RT effects that have previously been attributed to spatial attention (e.g., Abrams & Christ, 2003, 2005a, b, 2006; Franconeri & Simons 2003, 2005; Lin et al., 2008; Schmuckler et al., 2007; van der Weel & van der Meer, 2009; Takeuchi, 1997; von Mühlenen & Lleras, 2007), the motor priming account may also explain findings from brain imaging studies on how motion in depth is processed. Billington, Wilkie, Field, and Wann (2010) used fMRI to record BOLD activity as participants viewed an illusory ball that simulated forward or backward motion. The participants' task was to observe the ball as it rolled along a path containing two vertical bars located in a middle depth plane; at some point the ball disappeared and participants had to estimate the time at which it would have passed between the bars. Results showed that activity in several frontal and parietal cortical regions correlated with these estimates. However, judgments involving the looming ball were associated with increased activity in the superior colliculus (SC), a midbrain structure that is known to mediate some visual and motor functioning (e.g., Syka & Straschi, 1970). In humans it is involved in the generation of saccades (Schiller, 1977; Schiller, True, & Conway, 1979), and has also been implicated in the coding of some limb movements (Lünenburger, Kleiser, Stuphorn, Miller, & Hoffman, 2001; Stuphorn, Bauswein, & Hoffman, 2000). Other fMRI studies have shown that the premotor and sensorimotor cortices are involved in making time-to-collision judgments (e.g., Coull, Vidal, Goulon, Nazarian, & Craig, 2008; Field & Wann, 2005), thus it seems plausible that the sub-cortical and cortical networks involved in looming motion processing are to do with response preparation. It is worth noting, however, that all of the imaging studies cited above – as with many of the behavioural studies reviewed in the General Introduction – examined performance when motion was already attended. As such, their results provide an insight as to how these networks respond once motion has been selected by attention. We have yet to learn how these visuomotor networks respond to looming and receding motion when attention initially lies elsewhere in the visual field. A further issue is that the neural activation reported in such studies is only correlatory, whilst the data from the present study indicate that the relationship between looming motion and motor priming is causal.

The inference that visual looming motion acts upon the motor system may help elucidate the mechanisms underlying motion processing across the modalities. In the auditory domain, data have been reported that are consistent with the motor account we propose here. Bach, Neuhoff, Perrig, and Seifritz (2009) presented targets that were preceded by an auditory looming or receding sound cue, composed of tones that respectively increased or decreased in intensity over time. Targets following the looming sound cue were associated with shorter RTs and elevated skin conductance responses (SCR). Given that skin conductance levels reflect preparatory activity in the sympathetic nervous system, an enhanced SCR may be indicative of motor readiness and/or arousal rather than perceptual sensitivity to looming sounds. Other studies have shown that listeners overestimate the duration of looming sounds (Grassi & Darwin, 2006), underestimate their time-to-contact (Schiff & Oldak, 1990), and perceive them as louder (Neuhoff, 1998, 2001). Although these are ostensibly perceptual judgments of sound, it is possible that the subjective nature of these judgments may give rise to a response bias in favor of looming stimuli (Wittmann, van Wassenhove, Craig, & Paulus, 2010). Nevertheless, Neuhoff (1998, 2001) has speculated that the perceptual sensitivity to looming sounds is adaptive, as enhanced processing of such sounds would allow more time for an evasive response to be prepared. Indeed, the same outcome could be achieved without enhanced perceptual processing but with motor priming instead. One must be cautious, however, when comparing data across the auditory and visual modalities, as there exists no auditory counterpart to the irrelevant singleton paradigm used here. Consequently, there is no way to index performance in terms of the slope and intercept functions that characterize the looming advantage in the visual domain. As such, one is faced with the same issue as described above, where stimuli are presented in isolation and are consequently already attended. This is especially true of studies that have sought to directly compare perception of auditory and visual looming motion (Grassi &

Pavan, 2012), where stimuli would otherwise be poorly matched. It therefore remains to be determined whether the same post-attentional mechanisms are sensitive to auditory and visual looming motion, or whether distinct mechanisms have evolved to mediate cross-modal looming motion independently.

As it stands, models of visual search have thus far neglected the possibility that certain stimulus events can be prioritized after, rather than before or during, attentional selection. This is hardly surprising considering that in the real world, the very purpose of a visual search is to locate an object embedded somewhere in the environment, which is then terminated once the object enters visual awareness. Thus, models are primarily intended to describe the processes that mediate selection, whether these are largely top-down or bottom-up, or whether search is serial or parallel in nature, or hybridized between the two (Cave, 1999; Grossberg, Mingolla, & Ross, 1994; Hoffman, 1979; Humphreys & Muller, 1993; Itti & Koch, 2000; Thornton & Gilden, 2007; Treisman & Gelade, 1980; Tsotsos et al., 1995; Verghese, 2001; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Consequently, the role of the motor system in visual search modelling is usually restricted to the generation and guidance of saccades (e.g., Hamker, 2004; Pomplun, Reingold, & Shen, 2003). However, although post-attentional processes are given little prominence in visual search modelling, RT is often used as the primary measure in visual search experiments, and the success of a model can be evaluated by how well it predicts RT performance (Wolfe, Palmer, & Horowitz, 2010). A more complete understanding of the processes contributing to visual search RTs therefore requires consideration of those operating after selection has taken place. Simply put, an RT response may provide more than an approximation of when a target object enters visual awareness. It may also reflect a state of motor readiness that can be selectively induced by certain visual events but not others. In the present case, for example, a failure to consider all processing stages would lead to a mischaracterization of how looming motion acts upon the information processing system. That it is not prioritized ahead of receding motion at the point of selection would lead to the erroneous conclusion that all motion in depth is processed equally. While that may be true at the early perceptual stages of processing, it is evidently not the case in the later motoric stages.

There is one model of visual search that can accommodate the present findings. Wolfe, Cave, and Franzel's (1989) *guided search model* (see also Wolfe 1994, 1998, 2007, for revised versions) is a hybrid model in which attention is guided toward search items through a combination of pre-attentive parsing and top-down goals. Importantly, the hybrid aspect of this model, formally expressed as *asynchronous diffusion* (see Wolfe, 2007) allows serial and parallel processes to work in conjunction. Wolfe (2003; see also Wolfe, Oliva, Horowitz, Butcher, & Bompas, 2002; and Harris, Shaw, & Bates, 1979) illustrated this point by likening asynchronous diffusion to a carwash that is able to accommodate several cars at once even though they may arrive in series. Thus the speed at which an item passes through the system is dependent more on the efficiency of the "wash" than on the sequential order in which it arrives. Although the metaphor was used to elucidate the processes involved in and up to selection, the principle could also apply to post-attentional processes. That is, while the system might not distinguish between looming and receding motion at the point of entry, looming motion can be fast-tracked through the system once inside. The observation that looming and receding motion receive equal priority yet elicit different speeds of response may provide the first evidence of this. In order to fully understand the post-attentional processes that relate to visual search, then, the hypothetical processes described in Wolfe's metaphor may need to be formally incorporated into existing and future models.

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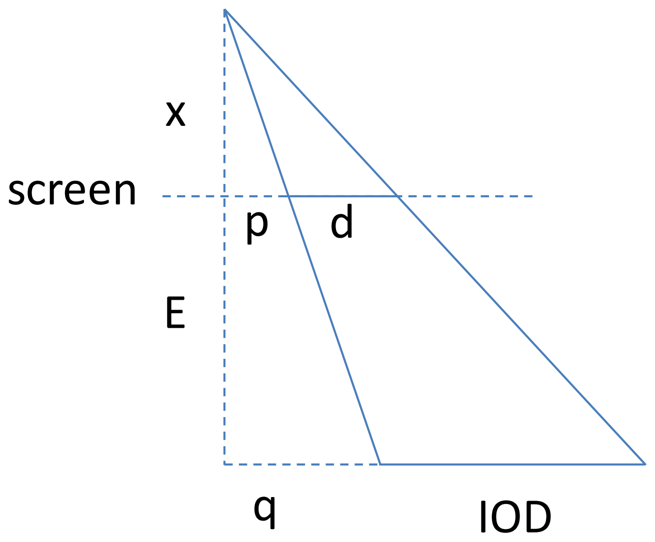
Footnote

1. At the request of an anonymous reviewer, all our RT data were reanalysed using a ±3SDs outlier criterion. This did not change any of the effects on which our conclusions are based. We therefore elected to keep the ±2SD criterion, thereby retaining consistency with our previously published study on this topic as well as the other studies we cite on looming motion and attention (e.g., Franconeri & Simons, 2003; von Mühlenen & Lleras, 2007).

2. This modification should not be confused with Theeuwes' (1991) use of arrays containing two unique singletons (see also Theeuwes, 1992, 1994). Theeuwes' interest was to examine whether bottom-up salience can be suppressed when it is task-irrelevant. As such, whereas a singleton on one dimension (e.g. colour) always indicated a target location, the singleton on another dimension (form) always served as a task-irrelevant distractor. The ability to suppress task-irrelevant salience was then assessed from target RTs in the presence or absence of the distractor. In the current Experiment 4, the two salient items were present on every trial and were equally likely to accommodate the target.

Appendix: Derivation of depth formula

Distance behind the screen



p/x=q/(E+x) -> p= qx/(E+x)
(d+p)/x=(IOD+q)/(E+x) substitute p
(d+ qx/(E+x))/x=(IOD+q)/(E+x) multiply both sides by x
d+ qx/(E+x)=x(IOD+q)/(E+x) multiply both sides by (E+x)
d(E+x)+qx=xIOD+qx Now qx drops out
d(E+x)=xIOD
x=Ed/(IOD-d)