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40 YEARS OF FEATURE INTEGRATION: SPECIAL ISSUE IN MEMORY OF ANNE TREISMAN

Axis of rotation as a basic feature in visual search

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Abstract

Searching for a "Q" among "O"s is easier than the opposite search (Treisman & Gormican in *Psychological Review, 95,* 15–48, 1988). In many cases, such "search asymmetries" occur because it is easier to search when a target is defined by the presence of a feature (i.e., the line terminator defining the tail of the "Q"), rather than by its absence. Treisman proposed that features that produce a search asymmetry are "basic" features in visual search (Treisman & Gormican in *Psychological Review, 95,* 15–48, 1988; Treisman & Souther in *Journal of Experimental Psychology: General, 114,* 285–310, 1985). Other stimulus attributes, such as color, orientation, and motion, have been found to produce search asymmetries (Dick, Ullman, & Sagi in *Science*, *237*, 400–402, 1987; Treisman & Gormican in *Psychological Review, 95,* 15–48, 1988; Treisman & Souther in *Journal of Experimental Psychology: General, 114,* 285–310, 1985). Other stimulus properties, such as facial expression, produce asymmetries because one type of item (e.g., neutral faces) demands less attention in search than another (e.g., angry faces). In the present series of experiments, search for a rolling target among spinning distractors proved to be more efficient than searching for a spinning target among rolling distractors. The effect does not appear to be due to differences in physical plausibility, direction of motion, or texture movement. Our results suggest that the spinning stimuli demand less attention, making search through spinning distractors for a rolling target easier than the opposite search.

Keywords Visual search · Search asymmetry · Axis of rotation · Basic features

Consider searching through a display for a red "T" among black "L"s. It will be intuitively clear that the red "T" will "pop out" from among the homogeneous black "L"s, making the search task very efficient. No matter how many "L"s are present, the uniquely colored "T" will capture attention. Color is a "preattentive feature" and can be used to guide attention. For almost half a century, we have known that much of our early visual processing occurs in parallel: This allows our visual system to efficiently process the enormous amount of information presented to it every second (Beck, 1982; Egeth, Jonides, & Wall, 1972; Julesz, 1984; Witkin & Tenenbaum, 1983). Building on this idea, Treisman and Gelade (1980) proposed that certain basic features (e.g., color) are processed in parallel and that a target defined by a salient instance of a basic feature will be found quickly, regardless of the number of distracting items in the display. This was what Treisman referred to as "pop-out."[1]

Parallel processing of basic features serves a role beyond supporting pop-out. Suppose that you are searching for the red "T" among black and red "L"s. Now the target will not pop out, but the preattentive processing of color remains useful. The color information will "guide" attention to red items, and an observer will be able to restrict search to that subset (Wolfe, 1992). The notion that a limited set of basic features can guide attention is at the heart of guided search (Wolfe, 1992, 1994;

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[1] A quick word about jargon. Color is a "basic" feature because it will support efficient search. However, not all color search will be efficient. A search for green amidst a slightly different green might be very inefficient. Efficient search requires a "salient" difference between the targets and distractors.

Wolfe, Cave, & Franzel, 1989) and related models (Moran, Zehetleitner, Müller, & Usher, 2013).

Evidence that a stimulus attribute can support pop-out and/or attentional guidance in search tasks is one piece of support for the hypothesis that the attribute is a preattentive feature. Treisman proposed that search asymmetries were another line of evidence (Treisman & Souther, 1985). Search asymmetries occur when search for stimulus A among stimulus B is more efficient than search for B among A. One of the classic examples is the search for the letter "Q" among "O"s, which is more efficient than the search for an "O" among "Q"s (Treisman & Gormican, 1988).

"Efficiency," as used here, refers to the slope of the function relating response time (RT) to the number of items in a search display (set size). A search for red amidst green would be highly efficient (resulting in a relatively flat slope of ~ 0 ms/item). A search for a "T" among "L"s (with all of the items being of the same color) would be inefficient (slopes of ~ 20–30 ms/item for target-present trials, and about twice that for target-absent trials). These results would be obtained for a search task in which observers did not need to fixate each item. If the "T"s and "L"s were small enough or ambiguous enough to require fixation in order to be identified, then target-present slopes would be ~ 125 ms/item, and target-absent trial slopes would be about 250 ms/item, because the rate of voluntary eye movements (~3–4 per second) is much slower than the rate of attentional processing of items that do not require fixation (~20–30 per second). We use the terms "efficient" and "inefficient" to describe search so as to avoid the more theoretically loaded terms "serial search" and "parallel search" (Wolfe, 1998, 2001). There are processes in the visual system that are serial and parallel, as we discussed above, but patterns of results of search experiments can be produced by various underlying processes (Townsend, 1990), so it is prudent to avoid the terms "serial search" and "parallel search" as short-hand descriptions of search slopes. "Efficient" and "inefficient" are imprecise terms. Slopes close to 0 ms/item are efficient, and slopes in the 20–40 ms/item range are inefficient for searches that do not require eye movements. As we noted above, search slopes will be much steeper if each item must be fixated or if extensive processing of individual items is required (e.g., search by non-Chinese speakers for one character among similar characters).

Returning to "O"s and "Q"s, Treisman argued that finding a "Q" among "O"s was more efficient than finding an "O" among "Q"s because the "Q" possessed a defining feature that was absent in the "O"s. In the case of a "Q" among "O"s, something like "line termination" would be the basic or guiding feature in visual search (Treisman & Souther, 1985). Search asymmetry is, thus, one of the markers of featural status. Evidence for search asymmetries has been used as evidence for the preattentive processing of color, speed, curvature, familiarity, orientation, line termination, luster, novelty, and faces (Ivry & Cohen, 1992; Malinowski & Hübner, 2001; Moraglia, 1989; Treisman & Gormican, 1988; Treisman & Souther, 1985; Wolfe & Franzel, 1988; Wolfe, Yee, & Friedman-Hill, 1992).

Search asymmetry is not unambiguous evidence for the presence of a basic, preattentive feature (Rosenholtz, 2001; Wolfe, 2001). In some cases, as Rosenholtz notes, the task itself may be asymmetric irrespective of the features. For instance, finding a moving target among stationary distractors is much easier than finding a stationary target among moving distractors. However, if the direction of motion is not constrained, the search for a stationary item is search for a target among heterogeneous distractors, whereas the search for motion is search among homogeneous distractors. Heterogeneity tends to slow search, regardless of the features (Duncan & Humphreys, 1989). In other cases, the speed of distractor rejection is a source of search asymmetry. Consider search for an angry face among neutral faces and a search for a neutral face among angry faces. Search for an angry target is more efficient than search for a neutral target (Hansen & Hansen, 1988). This has been taken as evidence that anger is a basic feature. However, if other basic features are controlled, search for one type of face among others is not efficient. Why might the search be asymmetrical? Treisman and Souther (1985) offered a plausible account that had to do with the speed of serially processing each stimulus (here, of each face). Suppose that it is a little harder to move attention away from a face once it is identified as angry. In a search for the neutral face, each distractor is angry. Each takes a little longer to process and, as a result, the slope of the RT × Set Size function—a measure of the cost per item—is steeper than search for angry among neutral items, in which neutral distractors can be dismissed more quickly.

Thus, one can explain asymmetric tasks as efficient search for the presence of a feature, as compared to less efficient search for the absence of that preattentive feature or as a consequence of slower distractor rejection for one type of distractor than for another. However, some asymmetries are not easily explained by either of these accounts. Wolfe (2001) described an example. In one condition of his study, participants searched for an upright silhouette of an elephant among inverted silhouettes. In the other condition, participants searched for inverted among upright elephants. The data showed a robust search asymmetry: It was easier to find an inverted elephant among upright ones than to find an upright elephant among inverted ones. Target-present slopes were just 5 ms/item when the target was the inverted elephant. It is not obvious what the feature might be or why upright distractors would hold attention so long. A similar result was obtained with camels, but not with swans or with a mixed collection of animals. We mention this particular odd result to support the conclusion that search asymmetries can be interesting and valuable, but that it is not always easy to uncover the forces that make some search tasks more efficient than others.

In the present work, we are interested in search asymmetries in visual search tasks defined by the motion of targets and distractors. Motion, like color and orientation, is a widely accepted basic, preattentive feature. As we discussed above, it is also one of the classic examples of a search asymmetry supporting the designation of a stimulus attribute as a basic feature. Dick (1989) found that searching for a moving target among stationary distractors was more efficient than searching for a stationary target among randomly moving distractors. As noted, Rosenholtz (2001) argued that this result could have come about due to the asymmetric design of the task. When the target is moving, the distractors are homogenously stationary, but when the target is stationary, the distractors are heterogeneously moving in different directions. In response, Royden, Wolfe, and Klempen (2001) used a symmetric design, by having all of the distractors move in the same direction, and found that the search asymmetry persisted. Ivry and Cohen (1992) found that searching for a fast target among slow distractors is more efficient than searching for a slow target among fast distractors. More recently, Horowitz, Wolfe, DiMase, and Klieger (2007) had observers search for targets that were wiggling along a line of motion among distractors that were moving linearly. This search was more efficient than the reverse situation. They also had observers look for wiggling targets with a clear translational component among distractors that wiggled about randomly, with no overall direction. Again, this was more efficient than the reverse situation. They argued that the attention-guiding processes had a preference for items that were moving across space and that rapid variation in the direction of that motion also guided attention.

Prior work on search for motion has focused on translational motion. The experiments reported below used the search asymmetry paradigm to examine search based on the axis of rotation. The items in these search tasks displayed either rolling or spinning motion, two forms of motion that can occur without translation. Rolling objects rotated about a horizontal axis (think of a piece of meat on a skewer, rotating over the fire), and spinning objects rotated about a vertical axis (think of a child's toy top—if children still have tops). How easy is it to search for an item that is rolling as opposed to spinning? Experiment 1 established that there is a search asymmetry between rolling and spinning complex objects that favors search for rolling stimuli. Experiment 2 replicated this effect using simplified stimuli (spheres). Experiments 3 and 4 investigated whether features of the experimental setup might have been driving this effect. Specifically, in Experiments 1 and 2 the objects lay on a virtual horizontal plane on which rolling stimuli might be expected to roll across the plane, while spinning stimuli might be expected to remain stationary. Experiment 3 moved all of the objects onto vertical planes. Experiment 4 addressed the physical plausibility of a motion: Spinning in place adheres to the laws of physics, but a rolling object should be either rolling toward or away from the observer. We found that neither the horizontal plane nor physical plausibility was driving this asymmetry. Finally, Experiment 5 ruled out 2-D texture motion instead of axis of rotation as the underlying cause. The basic search asymmetry favoring rolling stimuli persisted throughout each experiment except the final one, in which the percepts of rolling and spinning had been eliminated. Taken together, these experiments provide evidence that axis of rotation should be considered a guiding feature of visual attention.

General method

All experiments were conducted using the same equipment and procedural setup, with variations, as noted for each experiment.

Participants

Eighty-two total participants (54 females, 28 males) participated in these experiments at the Visual Attention Lab, Brigham and Women's Hospital. All participants gave informed consent and were compensated at a rate of $11/h. Informed consent procedures were approved by the Partners Human Research Committee. All participants had at least 20/25 vision with correction, all passed the Ishihara Color Blindness Test, and all were fluent speakers and readers of English.

Participants were excluded for performance of less than 85% correct. Three participants were excluded using this criterion (in Exp. 1, one participant; in Exp. 2, two participants).

The experiments described here were standard visual search experiments, in which the critical measures were RTs, the slope of the RT × Set Size functions, and, to a lesser degree, error rates. In our experience with experiments of this sort, the standard deviation of slope measures across observers is about 30% of the mean slope, and the standard deviation of RTs is about 40% of the mean RT. With these values, 11 observers are adequate to detect a 2× slope difference or a 100-ms RT difference with power = .9 and a Type I error of .05. We tested at least 12 observers per experiment.

Stimuli

The experiments were written in Unity 4.6.0f3 and were run on a 64-bit Avatar gaming PC. Stimuli were presented on a 55-in. TV (Sony XBR55). The resolution of the monitor was 4K, and the monitor had a 29-Hz refresh rate. Responses were entered via a Logitech F710 wireless gaming controller. Experiment 1 was presented in stereoscopic 3-D using polarized eyewear. Experiments 2–5 were presented in monoscopic 2-D.

The stimuli were designed and built in Blender and imported into Unity. They consisted of either complex objects (Exp. 1), spheres (Exps. 2–4), or flat circles (Exp. 5). Each object subtended between approximately 2.0 and 3.5 deg of visual angle, depending on their position in depth, as portrayed on the screen (see Fig. 1). Rolling objects rotated about a horizontal axis, spinning objects rotated about their vertical axis, and all axes were either parallel or perpendicular to the plane of the screen.

The display sizes were either four, eight, or 12 objects. On target-present trials, there would be only one target. Targets were present on half of the trials. On each trial, objects began rotating 250 ms after they appeared and rotated at a constant speed throughout the trial. The speeds and starting directions of object motion were randomly varied, with an average of 1.5 rotations per second and a range of 1–2 rotations/second, so the motion of the distractors did not appear uniform.

Procedure

In Experiments 1–4, we tested objects that were either spinning or rolling along their axis of rotation. In Experiment 5, we tested flat circles that had either a horizontally or a vertically moving texture. There were two conditions in each experiment. The only difference between the two conditions was which type of object was designated as the target, with the other type serving as the distractors. In two of the blocks, participants were asked to find a rolling target among spinning distractors, and they searched the opposite configuration in the other two blocks. There were 250 trials per condition, with four blocks overall. Each block started with an additional 12 practice trials. The order of the conditions was counterbalanced.

Before each experimental block, the target was identified to the participants, and they were shown examples of a rolling and a spinning object (Exps. 1–4) or of a vertically and a horizontally moving texture (Exp. 5). Participants were told to complete each trial as quickly as they could while minimizing errors. The responses were "present"–"absent." They pressed "A" on a standard video game controller if a target was present, and "B" if one was not. The display remained visible until they had made their response. Participants received feedback for their responses and were shown their scores (as numbers of correct answers) on the top left-hand side of the screen. Their score reset at the start of each new block.

In our analysis, we focused on search slopes as a measure of the RT × Set Size function, and used analysis of variance (ANOVA) and t tests to assess any significant differences between the conditions. Statistical tests on error rates were performed on the square-root arcsine-transformed data.

Experiment 1—Roll versus spin with complex objects

In Experiment 1 we used complex objects designed to produce strong, distinctive impressions of rolling and spinning.

Method

Eighteen participants (nine female, nine male) participated in Experiment 1. The stimuli were complex objects made from two rings and a sphere and were covered with a mottled blue texture. They were placed at random, nonoverlapping locations on a flat gray plane that extended away from the participant into the screen (see Fig. 1).

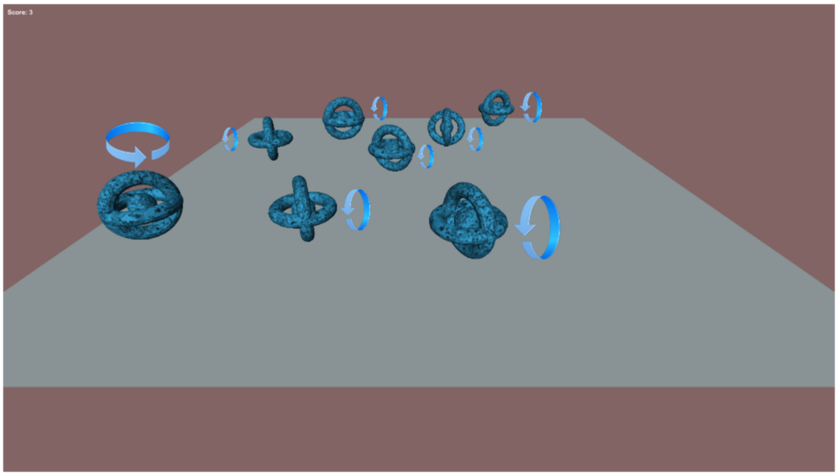

Fig. 1 Example display from Experiment 1. The stimuli consisted of complex objects with a blue texture. Participants were asked to find the rolling target among spinning distractors, or the spinning target among rolling distractors, depending on the condition. The blue arrows were not present in the experiment, and just indicate the observed motion—here, a spinning target at the front-left among rolling distractors. An animated version of the stimuli can be found at https://cabcs.medford.tufts.edu/owncloud/index.php/s/rfiSAPyU3o9JED9

Results and discussion

RTs were excluded from the analysis if they were less than 150 ms or greater than three *SD*s beyond the grand mean. This removed less than 1.4% of the data. The RT × Set Size functions can be seen in Fig. 2. There is clear evidence for a search asymmetry favoring search for the rolling target. The slopes appear to be shallower when the rolling item is the target, and the RTs appear to be faster. This is borne out in the statistical analysis. We found a main effect of condition (roll vs. spin) $[F(1, 17) = 29.44, p < .001, \eta_g^2 = .19]$, with spin slopes being significantly steeper than roll slopes, indicating that participants were slower in the spin condition and faster in the roll condition. This was confirmed by analyzing the RTs between the two conditions.

The overall RT was significantly longer in the spin than in the roll condition for target-present trials $[t(17) = 4.92, p < .001, d = 1.16]$ and for target-absent trials $[t(17) = 5.82, p < .001, d = 1.37]$. We also found the usual main effect of target presence $[F(1, 17) = 46.79, p < .001, \eta_g^2 = .44]$, with the target-absent slopes being steeper than the target-present slopes. There was an interaction between set size and condition $[F(1, 17) = 5.43, p = .032, \eta_g^2 = .03]$, reflecting the difference in slopes. Together, these results describe a robust search asymmetry, as is visualized in Fig. 2, with the roll-present condition being the fastest, most efficient search.

That being said, none of the RT × Set Size slopes are particularly efficient. The data for the roll-among-spin condition produced a slope of 15 ms/item for target-present trials. This is less efficient than the slopes found in classic "parallel" tasks (e.g., a red "T" among black "L"s), in which the slope is closer to 1–8 ms/item. The spin-among-roll condition produced a slope of 37 ms/item. This is comparable to classic "serial" search tasks of 20–30 ms/item (e.g., for a "T" among "L"s or a "2" among "5"s; Treisman & Gelade, 1980; Wolfe, 2001).

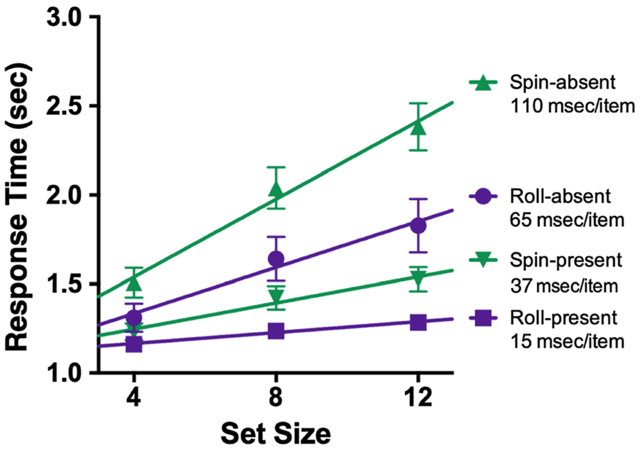

Fig. 2 RT × Set Size functions for Experiment 1 showing a clear asymmetry, with search for a rolling target being more efficient than search for a spinning target. Error bars show ± 1 *SEM*

The overall accuracy was near ceiling in both conditions, with spin being slightly worse than roll $[t(17) = 2.86, p = .01, d = 0.68]$, driven by a significant difference in accuracy between the conditions for set size 12 $[t(17) = 2.87, p = .01, d = 0.68]$ (see Fig. 3). We observed significant main effects of set size $[F(2, 34) = 3.82, p = .03, \eta_g^2 = .03]$, with errors increasing with increasing set size, and of target presence $[F(1, 17) = 63.43, p < .001, \eta_g^2 = .25]$, with more miss than false alarm errors. There was a significant interaction between set size and target presence $[F(2, 34) = 23.45, p < .001, \eta_g^2 = .08]$, with miss errors increasing with increasing set size to a far greater degree than false alarms. There were not any statistically significant interactions between condition and the other factors.

To summarize, in Experiment 1 we found a significant search asymmetry. Because we did not have an a priori hypothesis of the direction of the asymmetry, we conducted a replication with a monoscopic display and with simpler stimuli in Experiment 2.

Experiment 2—Roll versus spin with spheres

Method

A total of 16 participants (nine female, seven male) took part in Experiment 2. The key difference was the simplification of the display. Instead of complex objects, we used spheres with a dark gray texture (see Fig. 4), and instead of stereoscopic 3-D viewing, the displays were presented monoscopically (i.e., a typical computer display, with the same image presented to both eyes). The objects were once again placed at random locations on a flat grey plane that appeared to extend away from the participant into the screen.

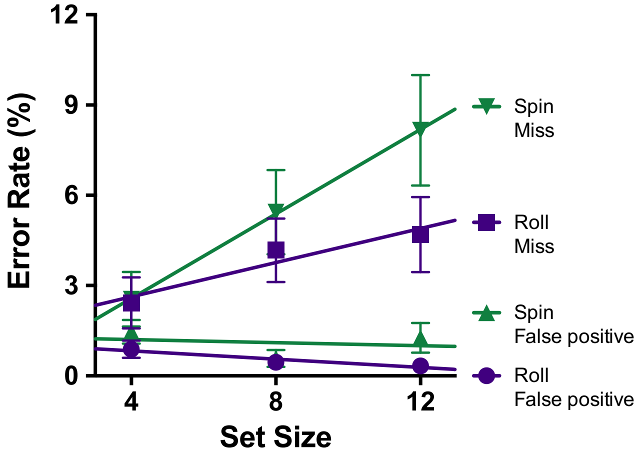

Fig. 3 Overall accuracy across participants in Experiment 1 for target-present and -absent trials for each visual set size and condition. Spin produces more errors than roll. Error bars denote the standard errors of the means

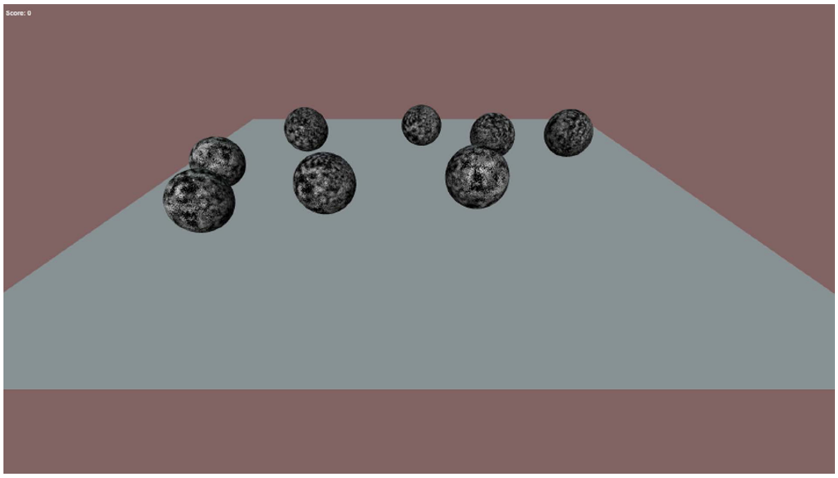

Fig. 4 Example display from Experiment 2. The stimuli consisted of either rolling or spinning spheres with a gray texture on a horizontal plane. Participants were asked to find the rolling target among spinning distractors, or the spinning target among the rolling distractors, depending on the condition. A movie of the stimuli can be found at https://cabcs.medford.tufts.edu/owncloud/index.php/s/rfiSAPyU3o9JED9

Results and discussion

RTs less than 150 ms or greater than three *SD*s over the grand mean were removed from the analysis. This removed less than 1% of all trials. As is shown in Fig. 5, participants were faster and more efficient in the roll-among-spin condition. This replicated the effects found in Experiment 1. For the slopes of the RT × Set Size interaction, there was a main effect of condition [$F(1, 15) = 8.53$, $p < .05$, $\eta_g^2 = .04$], with spin slopes being significantly steeper than roll slopes. We also found a main effect of target presence [$F(1, 15) = 48.52$, $p < .0001$, $\eta_g^2 = .33$], with target-present trials having faster RTs than target-absent trials, and no interaction. The overall RT (correct trials only) was significantly longer in the spin condition than in the roll condition [$t(15) = 3.75$, $p = .002$, $d = 0.94$].

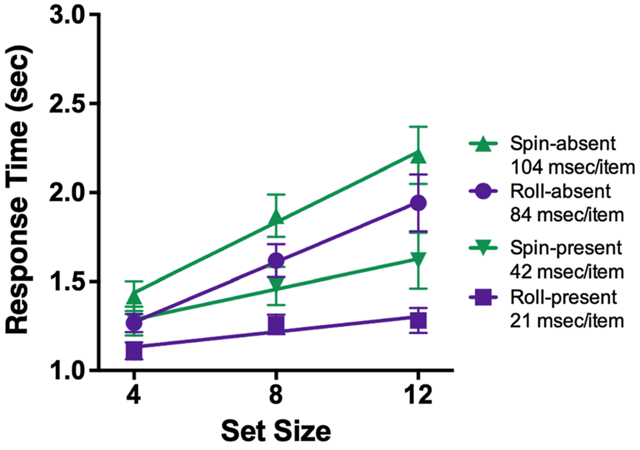

Fig. 5 Mean response times and search slopes across participants in Experiment 2 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means. Once again, the slopes for roll among spin were significantly shallower than those for spin among roll, suggesting more efficient search for a rolling target

We found no significant overall effect of accuracy, although spin was slightly (0.69%) worse. Breaking trials down by set size, condition, and target presence, we observed significant main effects of set size [$F(2, 30) = 9.35$, $p < .001$, $\eta_g^2 = .05$] and target presence [$F(1, 15) = 25.16$, $p < .001$, $\eta_g^2 = .25$], with an interaction between these factors [$F(2, 30) = 4.8$, $p = .016$, $\eta_g^2 = .03$], but no main effect or interactions with condition (see Fig. 6).

Experiment 3—Vertical roll versus spin

It is possible that this search asymmetry was dependent on the use of a horizontal plane. Rolling stimuli might have been expected to move on that plane in a way that spinning stimuli would not. For example, a rolling wheel would move across the field, whereas a spinning dancer might not. Thus, the

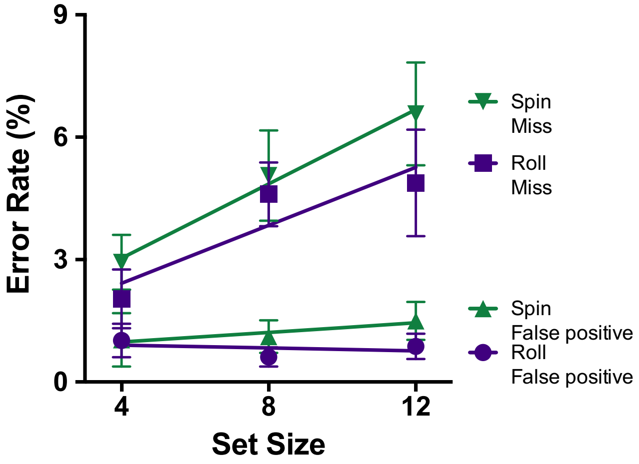

Fig. 6 Average error rates for the participants in Experiment 2 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means

horizontal plane of Experiments 1 and 2 might have created a difference in the perceived plausibility of the two forms of motion. In Experiment 3, we removed the horizontal plane and had all objects arranged on invisible vertical planes.

Method

Sixteen participants (14 female, two male) participated in Experiment 3. In this experiment, the only change from Experiment 2 was that the spheres were placed on an invisible vertical plane (see Fig. 7). The spheres looked as if they were suspended in space. Therefore, if the asymmetry were due to the effects of the horizontal plane on motion plausibility, the asymmetry should disappear.

Results

RTs less than 150 ms or greater than three *SD*s over the grand mean were removed from the analysis. This removed 1.1% of all trials. As Fig. 8 shows, there was still evidence for a search asymmetry when all items were presented on a vertical plane. For the slopes of the RT × Set Size function, we found a main effect of condition [$F(1, 15) = 4.89$, $p < .05$, $\eta_g^2 = .05$], with spin slopes being significantly steeper than roll slopes. There was also a main effect of target presence [$F(1, 15) = 21.54$, $p < .0005$, $\eta_g^2 = .30$], with target-present trials having faster RTs than target-absent trials, and a marginal interaction [$F(1, 15) = 4.21$, $p = .0582$, $\eta_g^2 = .02$]. The overall RT, computed for correct trials only, was significantly longer in the spin than in the roll condition [$t(15) = 3.54$, $p < .005$, $d = 0.89$]. The overall RT was also significantly longer in the spin than in the roll condition, in both target-present trials [$t(15) = 3.35$, $p < .005$, $d = 0.84$] and target-absent trials [$t(15) = 3.47$, $p < .005$, $d = 0.87$].

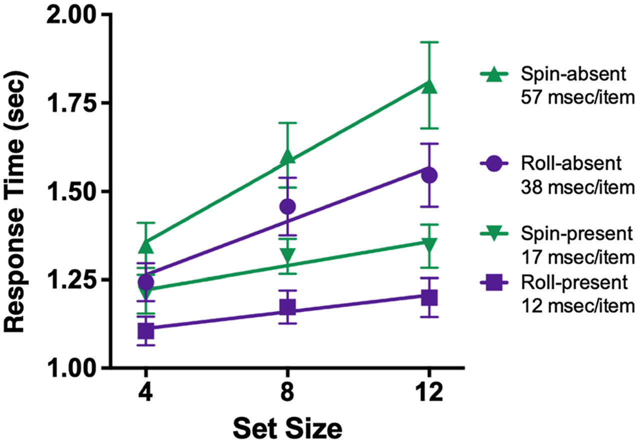

Fig. 8 Mean response times and search slopes across participants in Experiment 3 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means. Once again, search for roll among spin stimuli appears to be somewhat easier than search for spin among roll stimuli

Once again, participants were faster in the roll-among-spin condition, and especially so when the feature of interest was visible (i.e., target-present trials). This replicated the pattern of results found in Experiments 1 and 2. The difference between the slopes was less pronounced, although it still follows the same pattern as in the previous experiments. The slopes are also shallower, which suggests that this experiment was easier than the previous ones. Clearly, the horizontal plane was not generating the asymmetry.

We found no significant effect of accuracy, although the spin condition was slightly (1.1%) worse overall. Breaking trials down by set size, condition, and target presence, there was a significant main effect of target presence [$F(1, 15) = 103.76$, $p < .001$, $\eta_g^2 = .29$], but no main effect of set size or condition, or any significant interaction (See Fig. 9). This was a pattern similar to those in the previous experiments. As

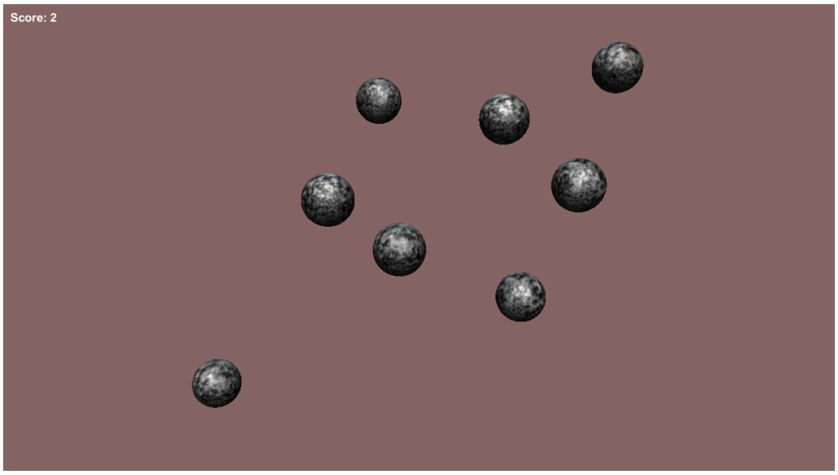

Fig. 7 Example display from Experiment 3. The stimuli consisted of either rolling or spinning spheres with a gray texture on an invisible vertical plane. Participants were once again asked to find the rolling target among spinning distractors, or the spinning target among rolling distractors, depending on the condition. A movie of the stimuli can be found at https://cabcs.medford.tufts.edu/owncloud/index.php/s/rfiSAPyU3o9JED9

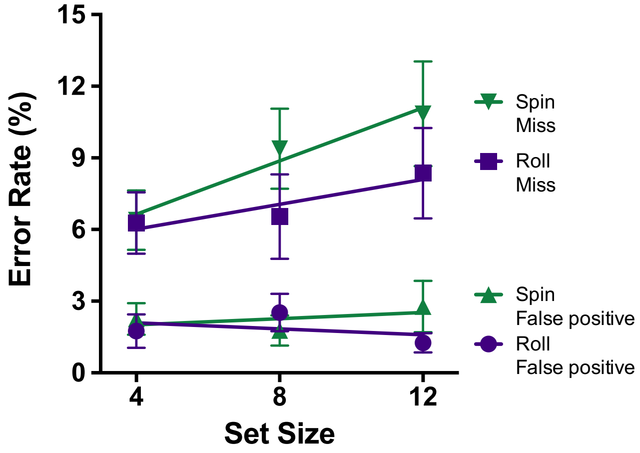

Fig. 9 Overall accuracy across participants in Experiment 3 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means

before, the pattern of errors did not run opposite to the pattern of RTs, arguing against speed–accuracy trade-off as an explanation of the search asymmetry favoring search for roll among spin stimuli.

Is the advantage for roll over spin a general advantage for roll, or is rolling forward the critical feature? There is some evidence that looming stimuli are treated differently than receding stimuli (Lin, Franconeri, & Enns, 2008; Skarratt, Cole, & Gellatly, 2009), so stimuli that are rolling toward the viewer might be more salient. In fact, as is shown in Fig. 10, stimuli rolling forward are the easiest targets to find. However, a one-way ANOVA on the slopes for the four directions of motion (forward, backward, left, and right) does not show a statistically reliable effect [$F(2.31, 34.61) = 2.020$, $p = .14$, Geisser–Greenhouse correction applied]. Dunnett's multiple comparisons test showed no significant difference between the forward motion condition and any of the other three motions.

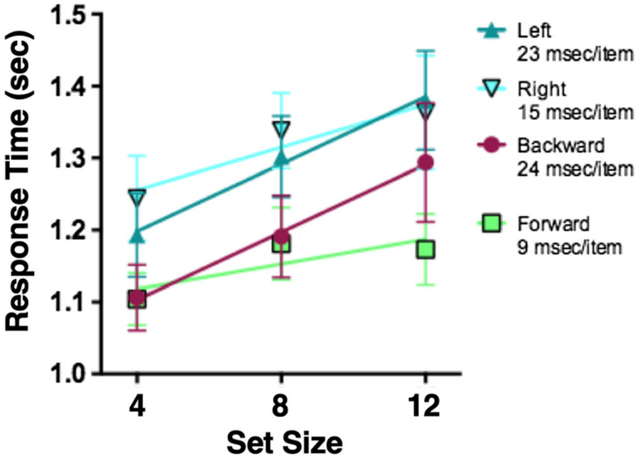

Fig. 10 Response times as a function of visual set size for each direction of motion in Experiment 3. Error bars denote the standard errors of the means. (Note the change in the *y*-axis scale from previous figures)

Experiment 4—Roll versus spin with rods

Perhaps the asymmetry reflects an asymmetry in the physical plausibility of the stimuli that was not eliminated in Experiment 3. As we noted, an item can sit on a surface and spin without changing its position on the plane. However, a rolling item would be expected to move either forward or backward. Even with the visible horizontal plane removed in Experiment 3, observers might have inferred invisible horizontal surfaces supporting the spheres. Experiment 4 modified the structure of the items to explicitly manipulate this factor of physical plausibility. Specifically, as is shown in Fig. 11, each sphere was pierced by a horizontal or vertical rod. If that rod were treated as the only physically possible axis of rotation, then a horizontal rod would be consistent with rolling motion, whereas a vertical rod would be consistent with spinning. If apparent violations of physics were the source of the asymmetry, then the asymmetry should go in opposite directions for vertical and horizontal rod stimuli (i.e., rolling would be more efficient than spinning for vertical rods, as before, but spinning would be more efficient than rolling for horizontal rods).

Method

Sixteen participants (12 female, four male) participated in Experiment 4. In this experiment, we elaborated on the displays from Experiment 3 by inserting a horizontal or vertical rod through the center of the spheres (see Fig. 11). The rods were 7.8 deg of visual angle long by 0.4 deg in diameter and were parallel to the plane of the display.

Results and discussion

RTs less than 150 ms or greater than three *SD*s over the grand mean were removed from the analysis. This removed 1.3% of all trials. This task produced somewhat slower RTs than the previous tasks. In particular, some observers probably fixated each item on target-absent trials, in order to confirm target absence.

Figure 12 shows the error and RT data. The hypothesis for this experiment was that rod orientation would change the physical plausibility of the rolling and spinning stimuli, and that this, in turn, would reverse the search asymmetry. This did not happen, though there is a hint that the advantage for rolling over spinning targets is smaller when the bar is vertical. In the vertical bar condition, the rolling items are physically implausible.

We performed a series of 2 × 2 ANOVAs with rod direction and condition as factors. When examining search slopes on target-present trials, we found no main effect of rod direction [$F(1, 15) < 0.01$, $p = .935$, $\eta_g^2 < .01$], but there was a significant main effect of condition [$F(1, 15) = 7.84$, $p = .013$, $\eta_g^2 = .13$], with rolling targets being found faster than spinning

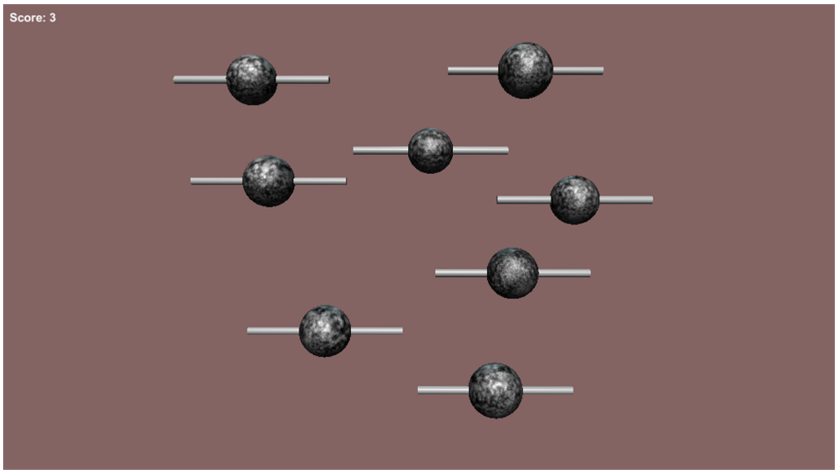

Fig. 11 Example display from Experiment 4, with a horizontal rod seeming to pierce the middle of each sphere. In half of the blocks, the stimuli were presented with an intersecting vertical rod, and in the other half, the stimuli were presented with an intersecting horizontal rod. A movie of the stimuli can be found at https://cabcs.medford.tufts.edu/owncloud/index.php/s/rfiSAPyU3o9JED9

targets, and a significant interaction between the factors [$F(1, 15) = 6.52$, $p = .022$, $\eta_g^2 = .022$], with the shallowest slope for rolling targets being in the horizontal rod condition (19 ms/item for horizontal vs. 29 ms/item for vertical), but the shallowest slopes for spinning targets being in the vertical rod condition (44 ms/item for vertical vs. 53 ms/item for horizontal). A similar pattern is seen in the miss error data. Although there were no main effects of either rod direction or condition (both ps > .05, both η_g^2s < .05), we did observe a significant interaction between the factors [$F(1, 15) = 8.994$, $p = .009$, $\eta_g^2 = .03$], with the lowest miss rate for rolling targets being in the horizontal rod condition (20.7% vs. 24.7%) and the lowest miss rate for spinning targets being in the vertical rod condition (24.2% vs. 29.1%).

Although this does suggest that something about physical plausibility might be guiding attention in the display, these results are precisely opposite those of the hypothesis that attention is guided to the item that apparently violates the physics of motion. Even this conclusion must be tempered by the results of the ANOVA for target-absent trials, which revealed

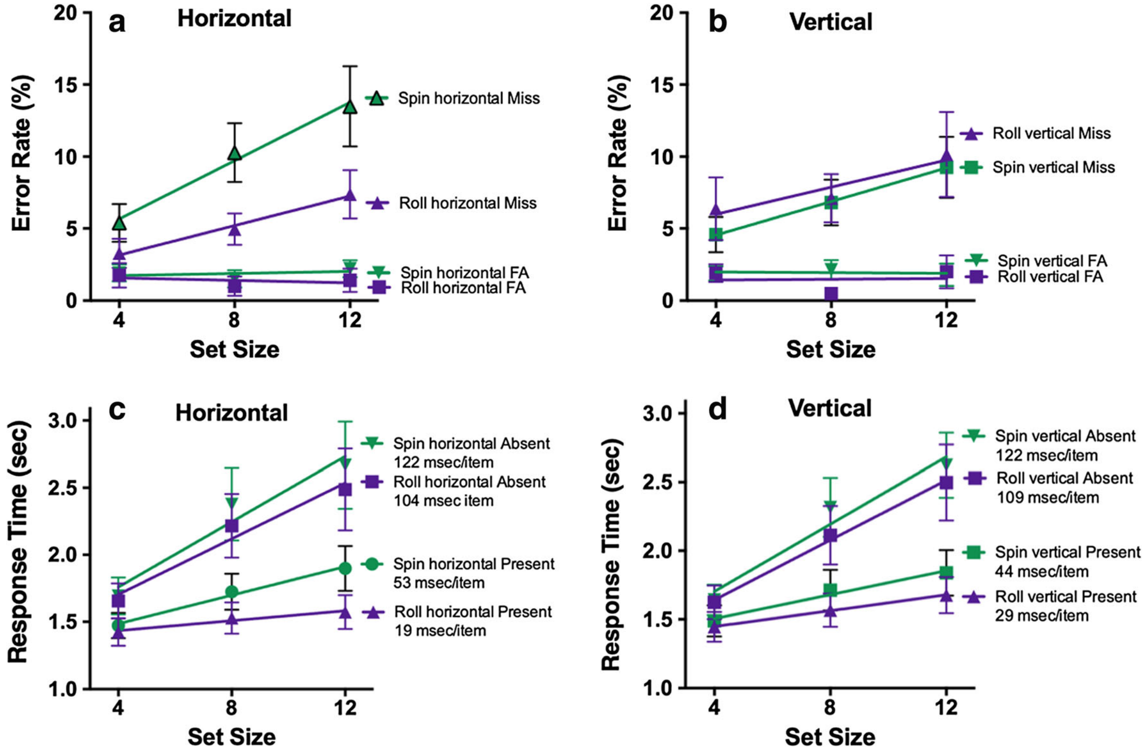

Fig. 12 Error rates and RT × Set Size functions for Experiment 4. Panels on the left show data for stimuli with a horizontal rod, whereas those on the right show results for stimuli with a vertical rod. Error bars show ± 1 *SEM*

no significant main effects or interaction (all *p*s > .05, all η_g^2s < .01). Similarly, with false alarm data, there was no significant main effect of rod direction or interaction between the factors (both *p*s > .5, both η_g^2s < .01), but only a significant main effect of condition, with roll trials being more accurate than spin trials.

Once again, participants were faster in the roll-among-spin condition, and also faster when the feature of interest (target-present trials) was present, for both the horizontal and vertical rod conditions. This replicated the effects found in Experiments 1, 2, and 3. The search asymmetry persisted, although the slopes were much shallower. This suggests that the rods made the experiment substantially more difficult in all conditions than in the previous experiments. However, since the pattern of results was the same, it appears that disruption of the laws of physics was not driving the asymmetry.

As is shown in Fig 12A, in the horizontal rod condition, search for roll was significantly more accurate than search for spin [$t(15) = 3.76, p = .002, d = 0.94$]. Breaking trials down by set size, condition, and target presence, there were significant main effects of set size [$F(2, 30) = 7.18, p = .003, \eta_g^2 = .04$] and target presence [$F(1, 15) = 47.98, p < .001, \eta_g^2 = .29$], with a significant interaction between these factors [$F(2, 30) = 16.82, p < .001, \eta_g^2 = .05$]. There was also a main effect for condition [$F(1, 15) = 12.17, p = .003, \eta_g^2 = 0.06$], but no significant interactions with this factor.

In the vertical rod condition, the roll and spin conditions were not significantly different [$t(15) = 0.24, p > .05, d = 0.06$] (see Fig. 12B). Breaking trials down by set size, condition, and target presence, we observed significant main effects of set size [$F(2, 30) = 5.18, p = .012, \eta_g^2 = .02$] and target presence [$F(1, 15) = 40.42, p < .001, \eta_g^2 = .24$], with an interaction between these factors [$F(2, 30) = 11.72, p < .001, \eta_g^2 = .04$], but no main effect or interactions with condition. This was the same pattern as in the previous experiments.

The primary effect of adding the bar seems to have been to make search somewhat less efficient in all conditions. But this did not erase or reverse the search asymmetry, which means that physical plausibility was not the primary driver of the search asymmetry.

Experiment 5—Vertical search (control)

In the prior experiments, rolling stimuli would create a vertical moving texture, while spinning stimuli would generate a horizontal, moving texture. In a final experiment, we tested whether this orientation cue was the source of the asymmetry. Static stimuli are shown in Fig. 13 (with a moving cartoon at https://cabcs.medford.tufts.edu/owncloud/index.php/s/rfiSAPyU3o9JED9). The stimuli are simple checkerboard patterns that move vertically or horizontally. They do not appear to be rolling or spinning.

Method

In Experiment 5, 16 participants (ten female, six male) participated. The stimuli were discs ranging from 2.8 to 3.3 deg of visual angle in diameter at a viewing distance of approximately 165 cm. Checkerboard textures moved vertically or horizontally across the discs at approximately 4 deg/s.

Participants were told to look for either a horizontally moving checkerboard texture among vertically moving checkerboard textures, or a vertically moveing checkerboard texture among horizontally moving checkerboard textures. A checkerboard texture was used instead of the gray texture from previous experiments because the grey texture on a flat circle still resembled a sphere. The checkerboard texture had a much flatter appearance.

Results and discussion

RTs less than 150 ms or greater than three *SD*s over the grand mean were removed from analysis. This removed 1.9% of all trials. Figures 14 and 15 show that, at most, only a hint of the search asymmetry remains. Search for horizontal targets is slightly faster than search for vertical targets, but this is not statistically significant. For the slopes of the RT × Set Size function, we observed no main effect of condition [$F(1, 15) = 2.02, p > .05, \eta_g^2 = .02$]. There was a main effect of target presence [$F(1, 15) = 20.02, p < .0001, \eta_g^2 = .31$], with target-present trials having faster RTs than target-absent trials, and an interaction between the two conditions [$F(1, 15) = 6.38, p = .02, \eta_g^2 = .02$]. Overall, the RT difference between the conditions was not significant [$t(15) = 1.18, p = .26, d = 0.295$]. There was also no significant effect of accuracy, with both conditions being near ceiling [$t(15) = 0.24, p = .81, d = 0.08$].

Unlike in the previous experiments, this experiment did not produce a search asymmetry. Critically, participants were not faster searching for the vertically moving texture (roll) among horizontally moving textures (spin). As can be seen in Fig. 14, the target-present slopes and the target-absent slopes for both conditions are efficient and practically lie on top of each other. This shows that 2-D texture movement was not driving the effect and that the axis of rotation was critical for producing the asymmetry.

It is interesting that the search for vertical among horizontal motion stimuli is as inefficient as it was in this experiment. Normally, search for vertical amidst horizontal stimuli (or horizontal amidst vertical stimuli) would be a very efficient "pop-out" search. This is true for the orientation of direction of motion (Driver, McLeod, & Dienes, 1992; McLeod, Driver, & Crisp, 1988), as well as for static oriented stimuli (Cavanagh, Arguin, & Treisman, 1990). It may be that there is a difference between search for the orientation of an item and search for an oriented pattern on the surface of an item (Alvarez & Cavanagh, 2008). Our observers were looking for the direction of motion on a

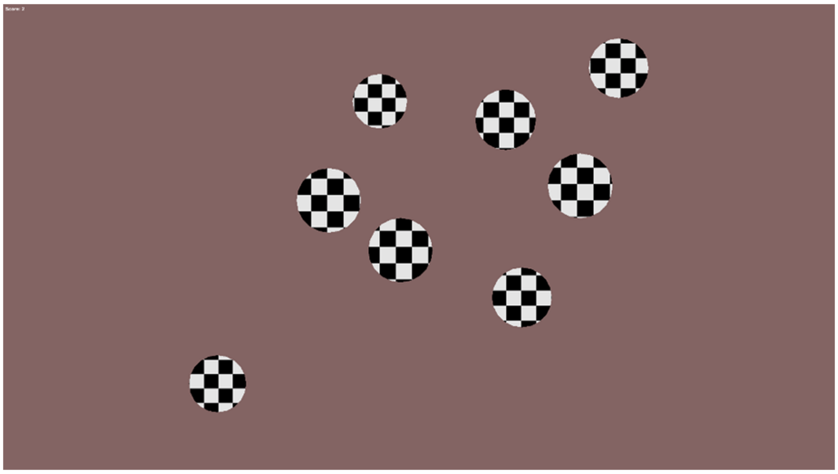

Fig. 13 Example display from Experiment 5. The stimuli consisted of either horizontal or vertical moving, flat checkerboard textures on a vertical plane. Participants were asked to find the horizontally moving texture target among vertically moving texture distractors, or the vertically moving texture target among horizontally moving texture distractors, depending on the condition

surface, and that appears to be a relatively inefficient, but not asymmetric, search.

General discussion

Across the experiments reported here, we found a persistent search asymmetry, with rolling among spinning objects being found more quickly than spinning among rolling objects. This effect is not restricted to items of specific shapes (Exps. 1 and 2), to items on a horizontal plane (Exp. 3), or to items that are physically plausible (Exp. 4). The effect does seem to be based on the apparent rotation of objects rather than on vertical versus horizontal motion in a 2-D plane (Exp. 5).

Does this mean that axis of rotation is a basic "preattentive" feature? Since Treisman introduced the idea (Treisman & Gormican, 1988; Treisman & Souther, 1985), search asymmetries have been one of the more useful diagnostics of basic feature status. In the simplest form, it is easier to detect the presence of a feature among its absence than to detect the reverse arrangement. Thus, a moving stimulus is easier to find among static distractors than a static stimulus among moving distractors (Dick et al., 1987) because, by this argument, motion is the feature. It is not clear why "roll" would count as the feature in the present case. Moreover, if the presence of a salient basic feature defines a target, then the resulting search should be quite efficient. In the results reported here, search for roll among spin stimuli was more efficient than for spin among roll stimuli, but it was not particularly efficient. Across Experiments 1–4, the roll-among-spin target-present slopes were quite consistently in the range of 15–20 ms/item. This is more characteristic of relatively inefficient "spatial configuration searches" than it is of efficient "feature," or even "conjunction," searches (see Fig. 6 of Wolfe, 1998).

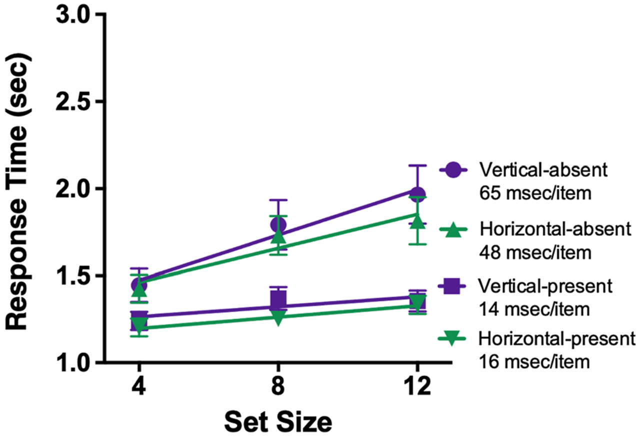

Fig. 14 Mean response times and search slopes across participants in Experiment 5 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means

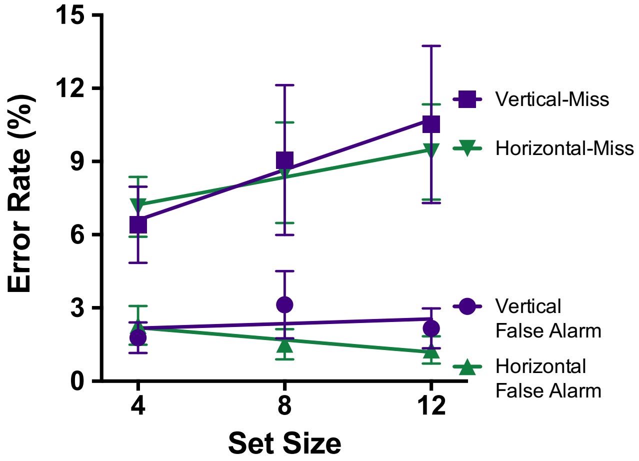

Fig. 15 Overall accuracy across participants in Experiment 5 for target-present and -absent trials for each visual set size and condition. Error bars denote the standard errors of the means

As we noted in the introduction, there is an alternative route to search asymmetry, proposed by Treisman and Souther (1985, p. 292): Suppose that a search proceeds serially, one item after the other, and that it takes longer to reject one type of distractor than the other. A classic example is search for a letter among mirror-reversed letters, and a mirror-reversed letter among letters (Frith, 1974; Reicher, Snyder, & Richards, 1976; Richards & Reicher, 1978; Zhaoping & Frith, 2011). We process familiar letters quickly, but inverted or mirror-reversed letters take longer. As a result, if you search for a mirror-reversed target, each regular letter will be processed quickly, and search will be more efficient than if you search for a normal letter among mirror-reversed letters. Results like this have been used to argue that "novelty" is a feature (Hawley, Johnston, & Farnham, 1994; Johnston, Hawley, & Farnham, 1993; Wang, Cavanagh, & Green, 1994), because search for novel among familiar is more efficient than search for familiar among novel objects. The issue is not completely clear (see the review in Wolfe, 2001), but when both searches are inefficient, it is probably more plausible to see the asymmetry as arising from faster processing of one type of distractor.

In the present work, this distractor-processing account proposes that spinning distractors were easier to reject as nontargets than rolling distractors. That would make it easier to find the rolling target. It is not obvious why observers should reject spinning distractors more fluently. In face search, it is generally easier to find an angry among neutral faces than is the opposite search (Hansen & Hansen, 1988; Lundqvist, Bruce, & Öhman, 2015). This effect is controversial (Horstmann, Bergmann, Burghaus, & Becker, 2010; Purcell, Stewart, & Skov, 1996), but assuming it to be real, one way to explain it would be to argue that angry faces hold attention for a little longer than neutral faces do. Thus, it is harder to reject angry distractors, slowing the search for the neutral face target. Why might rolling stimuli hold attention longer? Perhaps they imply lateral motion in a way that spinning stimuli do not. This would be a more compelling argument if the rods in Experiment 4 had convincingly abolished or reversed the effect. The rods might have been expected to interfere with the implied lateral motion of the rolling items, but although the rods modulated the effect, the basic asymmetry appears to have remained.

We are left with a robust asymmetry, but not with a robust explanation of that asymmetry. This turns out to be somewhat characteristic of the search asymmetry literature. Returning to letters, for example, why is search for "N" among mirror-"N"s more asymmetric than search for "P," "K," or lowercase letters such as "f" among their mirrors (Shen & Reingold, 2001; Wolfe, 2001)? Lowercase "y" and mirror-reversed "y," for instance, produce almost no asymmetry (Wolfe, 2001). With silhouettes of animals, Wolfe (2001) showed that an inverted elephant is easier to find among upright elephants than is an upright among inverted elephants. The effect is somewhat bigger with camels, but it is all but absent with swans. The reasons are unclear. Random inverted animals are easier to find among upright animals than upright animals among inverted animals , but all of the searches are quire inefficient. This suggests that it is easier to process upright animal silhouettes, but there are other factors that we simply do not understand.

Search asymmetries remain a valuable tool in visual search research. The present set of experiments has uncovered a new example of an asymmetry. The advantage in finding rolling stimuli tells us that different directions of rotational movement are processed somewhat differently. Further research will be required in order to fully understand the nature of that difference. For example, only two axes of rotation were explored in this article. An object could be rotating around the line of sight or, for that matter, around intermediate axes. It would be informative to explore the space of rotating stimuli more extensively as we seek to understand search based on the motion of an object.

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