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Shape Beyond Recognition: Form-Derived Directionality and Its Effects on Visual Attention and Motion Perception

Heida M. Sigurdardottir, Suzanne M. Michalak, and David L. Sheinberg
Brown University

The shape of an object restricts its movements and therefore its future location. The rules governing selective sampling of the environment likely incorporate any available data, including shape, that provide information about where important things are going to be in the near future so that the object can be located, tracked, and sampled for information. We asked people to assess in which direction several novel objects pointed or directed them. With independent groups of people, we investigated whether their attention and sense of motion were systematically biased in this direction. Our work shows that nearly any novel object has intrinsic directionality derived from its shape. This shape information is swiftly and automatically incorporated into the allocation of overt and covert visual orienting and the detection of motion, processes that themselves are inherently directional. The observed connection between form and space suggests that shape processing goes beyond recognition alone and may help explain why shape is a relevant dimension throughout the visual brain.

Keywords: shape, direction, attention, eye movements, motion

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The visual world is not static; within it, things are moving, and we are often moving ourselves—if not our bodies, then at least our eyes, which constantly scan the visual scene. Processing dynamic input requires efficient extraction of information about the current state of the environment to make predictions about where important things will be in the near future. We should guide our eyes and attention not to an object's previous location, but to where it is likely to be once action can be taken. Fortunately, under normal circumstances, an object does not randomly change location from one moment to the next; its future state depends on its past state. An optimized system would be able to use such information to accurately predict an object's future location or motion path from a single snapshot in time. This could bias both overt and covert visual orienting so that objects can be located, tracked, and sampled even in a dynamic world. Here we test the hypothesis that information derived from an object's shape enables the brain to make such inferences.

Within the visual system, the dorsal pathway's role in visual orienting, tracking, and motion analysis is well established (Andersen, 1997; Colby & Goldberg, 1999; Mountcastle, Lynch, Georgopoulos, Sakata, & Acuna, 1975; Ungerleider & Mishkin, 1982; Van Essen & Gallant, 1994). In addition, some regions of the dorsal stream are responsive to the shape of objects (Grill-Spector & Malach, 2004; Janssen, Srivastava, Ombelet, & Orban, 2008; Konen & Kastner, 2008; Lehky & Sereno, 2007; Murata, Gallese, Luppino, Kaseda, & Sakata, 2000; Oliver & Thompson-Schill, 2003; Red, Patel, & Sereno, 2012; Sakata et al., 1998; Sakata, Taira, Murata, & Mine, 1995; A. B. Sereno & Amador, 2006; A. B. Sereno & Maunsell, 1998; M. E. Sereno, Trinath, Augath, & Logothetis, 2002; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990). The fact that shape selectivity exists in cortical areas beyond the ventral visual stream (Desimone, Albright, Gross, & Bruce, 1984; Gross, Rocha-Miranda, & Bender, 1972; Logothetis & Sheinberg, 1996; Tanaka, Saito, Fukada, & Moriya, 1991) argues against regional specialization for particular stimulus attributes, emphasizing the need to consider function and goal in relation to object properties. Shape information might be integrated with various other cues and tailored to a particular process or task. Indeed, the shape of an object influences processes thought to depend on the dorsal visual stream, such as visual orienting and estimation of motion, in addition to object recognition and categorization, which are classically linked with the ventral visual stream.

For example, the oculomotor system seems able to take into account the global shape of an object during saccade planning (He & Kowler, 1991). This kind of visual orienting does not merely depend on low-level averaging of visual elements, but has access to a higher level representation of the object's shape (Melcher & Kowler, 1999). This shape information may be partially or wholly independent from the representation used for perception (Vishwanath, Kowler, & Feldman, 2000). The shape of an object guides overt and covert attention within the object itself and can, in

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Heida M. Sigurdardottir, Suzanne M. Michalak, and David L. Sheinberg, Department of Neuroscience, Brown University.

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Correspondence concerning this article should be addressed to Heida M. Sigurdardottir, Department of Neuroscience, Brown University, Box G-LN, Providence, RI 02912. E-mail: heidamaria@gmail.com

special cases, push attention away (Driver et al., 1999; Fischer, Castel, Dodd, & Pratt, 2003; Friesen & Kingstone, 1998; Hommel, Pratt, Colzato, & Godijn, 2001; Kuhn & Kingstone, 2009; Tipples, 2002, 2008). An arrow is a prime example. Despite initial thoughts to the contrary (Jonides, 1981), arrows automatically bias orienting (Hommel et al., 2001; Kuhn & Kingstone, 2009; Tipples, 2002, 2008). This may be partially due to repeated association of this particular shape and its referent; something often appears in the direction to which an arrow is pointing. Here we argue that this association is not arbitrary; initially, the symbol might have been selected because its shape already had an inherent directionality that automatically evoked an orienting bias. This bias might again be derived from the fact that the structure of a real arrow facilitates a stable flight path in a single direction. In general, the shape of objects constrains their movements. It would therefore be beneficial for the visual system to use shape information to predict an object's probable motion path and to use such predictions for overt and covert visual orienting.

Shape or form cues are integrated into motion calculations (see Kourtzi, Krekelberg, & van Wezel, 2008, for a review). For example, the oriented trace or streak left by a fast-moving object determines its perceived axis of motion (Burr & Ross, 2002; Geisler, 1999). Dynamic Glass patterns, which contain no coherent motion, can also lead to the perception of movement and affect the tuning of motion selective neurons (Krekelberg, Dannenberg, Hoffmann, Bremmer, & Ross, 2003; Krekelberg, Vatakis, & Kourtzi, 2005; Ross, Badcock, & Hayes, 2000). Likewise, still photographs depicting objects in motion evoke greater activation in motion selective cortical regions than photographs of stationary objects (Kourtzi & Kanwisher, 2000; Senior et al., 2000). An object's remembered location is also shifted along its implied path of motion (Freyd & Finke, 1984). This shift is lost when motion-selective cortical regions are temporarily deactivated (Senior, Ward, & David, 2002). With some exceptions (e.g., Caplovitz & Tse, 2007; Tse & Logothetis, 2002), most studies on the effects of form or shape cues on motion involved simple non-object-like stimuli (e.g., motion streaks, Glass patterns), or recognizable animate or inanimate objects or scenes depicting familiar events or actions.

The studies described in this article were stimulated by the idea that shape information existing in dorsal stream regions is tailored to and supports the function of these areas in spatial perception and action guidance (Goodale & Milner, 1992; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982). We explore the role of shape information in visual orienting and motion calculation that have well-known neural substrates in the dorsal stream. In Experiments 1 and 2, we establish that people consistently deem novel shapes to "point" in particular directions. We then look at the effects of this shape-derived directionality on visual orienting (Experiments 3, 4, and 7) and motion perception (Experiments 5–7).

Our work shows that objects have intrinsic directionality derived from their shape. This shape information is swiftly and automatically incorporated into the allocation of overt and covert visual orienting and the detection of motion, processes that are inherently directional. Although covert attention might be split under some unusual circumstances (Awh & Pashler, 2000; Hahn & Kramer, 1998; Kramer & Hahn, 1995), our eyes only move in one direction at a time. Likewise, a single object only moves in one direction at any given time point. Attention is automatically pushed away from the object in a direction that depends on the object's shape. This in turn is incorporated into the calculation of the object's probable path of movement; detection of an object's direction of motion is facilitated if it is congruent with the inherent shape-derived directionality of the object and hindered if shape directionality and motion directionality oppose each other. Importantly, such form-dependent directional biases are not limited to well-known or overlearned objects or tasks. Instead, they are seen for meaningless shapes, with which people have no prior experience, in a variety of settings and regardless of whether people have any intent or reason to use this directional information. This suggests that shape-related directional biases are ever present and are given weight in predictions or simulations of the upcoming state of the environment or, more specifically, where important objects will likely be located in the immediate future.

Experiments: Methodological Overview

One hundred and fourteen people participated in one of seven experiments. Each person took part only once. They reported normal or corrected to normal vision and were paid for their participation. All participants gave their written consent. The experimental protocol was approved by Brown University's institutional review board.

The experiments were controlled by a computer console running on the QNX real-time operating system (QSSL; QNX Software Systems). It communicated with a Windows XP PC through a direct high-speed Ethernet connection. This computer ran custom-made software based on OpenGL for graphics display. In Experiments 1–3, stimuli were shown on a standard 20-in. (50.8-cm) cathode ray tube monitor (width: 41 cm; height: 30 cm) with 1024×768 resolution. In Experiments 5–7, they were shown on a high-speed 23-in. (58.42-cm) widescreen LCD monitor (width: 51 cm; height: 28 cm) with 1920×1080 resolution. In Experiment 4, half of the participants were run with the former setup, and half the latter. The monitors' vertical refresh rate was 100 Hz for all experiments. The displays were placed at a distance of 57 cm in front of the participants.

Participants were seated in a dark, quiet room in front of a computer screen. A black curtain was draped around them and the computer screen. Participants' heads were held still by a chin rest. In Experiments 3, 4, and 7, people's eye movements were monitored with an EyeLink 1000 eye tracker (SR Research). A high-speed camera and an infrared light source were desk-mounted under the computer monitor. Eye gaze was monocularly recorded at 1,000 Hz. The analog signal was sampled and digitized at 200 Hz. The eye tracker was calibrated by asking participants to saccade to and fixate several small targets that appeared in random locations on the screen. Eye tracking was not performed in Experiments 1, 2, 5, and 6.

An alpha level of .05 is assumed for all statistical analysis of the data. Statistical tests are two-sided. Results are Greenhouse–Geisser corrected for deviations from sphericity when Mauchly's test of sphericity is significant. Effect sizes are estimated with Pearson's r, Cohen's d (mean difference/standard deviation of difference), and partial eta-squared. Error bars represent 95% confidence intervals for within-subject comparisons and are calculated with Cousineau's (2005) method with the correction described by Morey (2008).

Experiment 1: Directionality Assessment

The aim of Experiment 1 was to assess the extent to which people agree on the directionality of objects based on their shape alone. We did not want to constrain the interpretation of our results with our preconceptions about what might make a shape directional. We therefore constructed a variety of random shapes with which people had no previous experience and empirically determined their directionality. We asked people to judge where each of the novel shapes pointed or directed them and determined whether people's judgments were more similar than would be expected by chance. If judgments of a majority of the shapes deviate from circular uniformity, we would conclude that directionality is a general property of a wide variety of shapes.

Method

Participants. Sixteen people (nine women, seven men) participated in this experiment. Their ages ranged from 18 to 36 years ($M = 25$).

Stimuli. Eighty novel shapes were generated by superimposing two filled polygons. Each polygon was made by fitting a spline to randomly generated coordinates (eight for simple or 16 for complex shapes) on a two-dimensional plane. The algorithm was based on the General Polygon Clipper library (Version 2.32), which is freely available for noncommercial use (Murta, 2000; see also Vatti, 1992). Shapes were scaled to an equal area. Their diameter was approximately 4°. Of the 80 shapes, 20 were made symmetrical by reflecting one side around the *y*-axis. The contours of the shapes were densely sampled and translated so that the means of their contour coordinates would coincide. Each shape was randomly rotated around this pivot and kept this rotation throughout the experiment and for all participants. The same method was used to make additional shapes for a short practice session. All shapes were shown as white, filled silhouettes. The shapes can be seen in Figure 1.

Design. Each person completed 360 trials, out of which 40 were control trials and 320 were experimental trials (80 shapes × 4 repetitions). The trials were spread across five blocks and were shown in a randomized order with the constraint that eight control trials were shown in each block.

Procedure. People were instructed to look to the center of the screen at the beginning of each trial. A single central shape and a surrounding gray circle (diameter 26°) were presented on a black background. The shape was on for 100 ms, but the circle stayed visible throughout the trial. The task is depicted in Figure 2.

People used a computer mouse to drag a gray line in the direction to which they thought the shape pointed or directed them; longer lines indicated stronger confidence. The line was drawn in real time from the screen center to the current position of a gray circular cursor (diameter 0.4°) and could be drawn as far as to the surrounding circle. Participants clicked the left mouse button to indicate their response. They were encouraged not to think much about their responses but instead to go with their intuition.

In a minority of trials, no shape was shown and participants instead dragged a line to the position of a small disk. All participants performed well on these control trials, ensuring us that they paid attention to the task at hand and could position the line appropriately. Before beginning the experiment, people completed a short practice block.

Results

Each of the 16 participants judged the direction of each shape four times, giving a total of 64 data points for each of the 80 random shapes. Example shapes with their directional judgments can be seen in Figure 3.

We tested for circular uniformity of the directional judgments of each shape. Visual inspection of the click endpoints indicated that some of the shapes were unidirectional, some were bidirectional, and yet others were multidirectional. We therefore performed two statistical tests on each shape: A Raleigh test and Rao's spacing

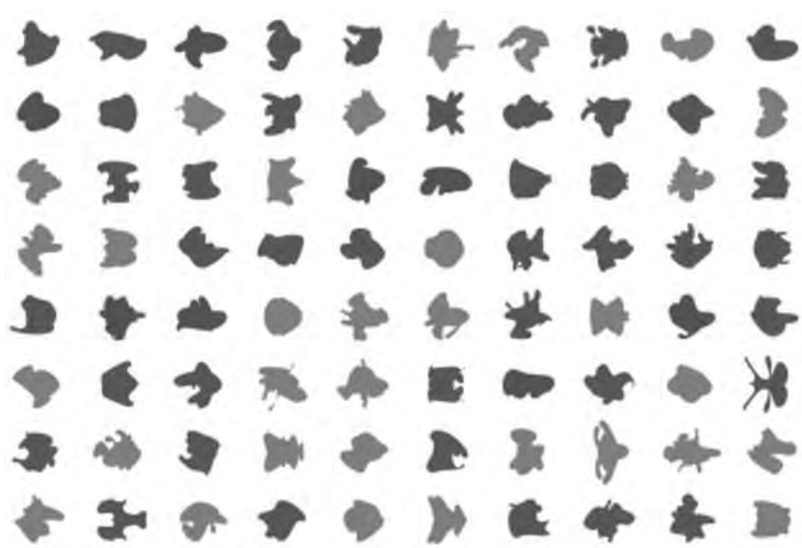

Figure 1. All novel shapes. Shapes are shown pointing to the right, as judged by people in Experiment 2. All novel shapes were used in Experiments 1 and 2. Red and orange shapes were used in Experiments 3, 5, 6, and 7. Red shapes were used in Experiment 4. Shapes were not shown in color during the experiments.

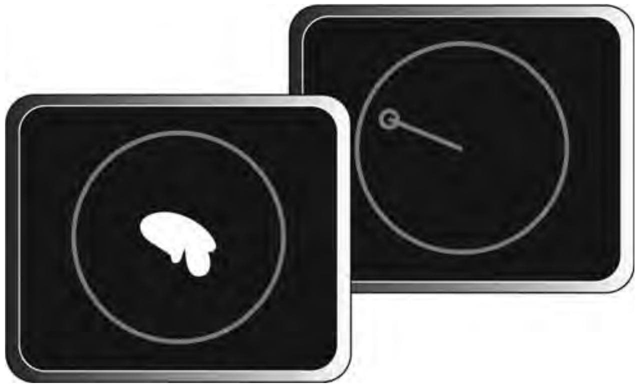

Figure 2. Task in Experiment 1. People judged the directionality of novel shapes by dragging a line in the direction to which they thought the shapes pointed or directed them.

test. The Raleigh test assumes that the samples are drawn from a von Mises distribution (analogous to the normal distribution for noncircular data) and is useful for detecting deviations from uniformity when a shape has one main direction (Berens, 2009). Rao's spacing test can detect deviations from a uniform distribution for shapes that are neither unidirectional nor axially bidirectional (Berens, 2009).

A participant's decision criterion for assigning directionality could evolve over the course of the experiment. For each shape, we therefore tested for significant deviations from circular uniformity using only the first directional judgment of each participant. Instead of using all 64 judgments, we therefore only used 16 data points per shape, effectively lowering our statistical power. Despite this rather conservative way of analyzing the data, the Raleigh test rejected the null hypothesis that the drag-and-clicks were uniformly distributed for 42 out of 80 shapes. Rao's spacing test was significant for nearly all of the shapes, or 71 out of 80. We therefore conclude that novel, random shapes in general are directional. A majority of completely novel shapes has an inherent directionality, be it unidirectional, bidirectional, or multidirectional. Figure 1 in the supplemental materials shows our entire shape set and the corresponding directionality judgments from Experiment 1. Figure 2 in the supplemental materials shows all directional judgments from Experiment 1, regardless of shape. Test statistics can be found in Tables 1 and 2 in the supplemental materials.

Experiment 2: Forced Choice of Directionality

Experiment 1 showed that directional judgments are nonuniform for a majority of randomly shaped novel objects. However, judgments also appeared to be influenced by factors that were independent of, or interacted with, the shape of these objects (see supplemental materials, Figure 2). Even if the rotation of the shapes was randomly determined, people in general tended to favor an upward and, to some lesser extent, a downward direction. People might have been following a heuristic akin to "when in doubt, an object is aligned to the axis of gravity." The benefits of transient visual attention have also been documented to be greater in the upper than the lower visual hemifield (Kristjánsson & Sigurdardottir, 2008), and this could be a contributing factor. It is also possible that the response mode introduced some bias. To minimize such biases, Experiment 2 involved a more constrained judgment about the directionality of the same shapes with a new set of participants.

The main purpose of Experiment 2 was to get unbiased measurements of each shape's perceived directionality so that these measures could be used as predictors of behavior in Experiments 3–7. We also wanted to know whether we could assume that directionality was independent of the time of probing. Neurons within dorsal stream regions important for the allocation of attention and eye movements respond selectively to shapes, but these shape responses can change very rapidly over the course of a few hundred milliseconds (H. M. Sigurdardottir & D. L. Sheinberg, unpublished observations). We therefore thought it possible that the perceived direction of a shape could change very rapidly as well and thus we included two stimulus onset asynchronies (SOAs) in this experiment.

Method

Participants. Fourteen new participants (nine women, five men) completed Experiment 2. They were between 18 and 31 years of age ($M = 23$).

Stimuli. The 80 shapes used in Experiment 1 were also used in Experiment 2. We found the median axis of the directional estimates gathered for each shape in Experiment 1. Note that the axis itself has an orientation but not a direction; for example, directional judgments to the left and right would similarly favor a horizontal axis, and up and down directional judgments would count toward a vertical axis. All shapes were then rotated so that this main axis fell on the horizontal meridian. Clockwise or anticlockwise rotation was chosen for each shape, whichever one led to a rotation of fewer degrees from the shape's orientation in

Figure 3. Example shapes and directional judgments. Several novel shapes are shown with the endpoints (white circles) of people's drag-and-clicks used for directional judgments in Experiment 1.

Experiment 1. Each shape was shown in this alignment (original) or reflected across the vertical meridian (mirrored).

Design. Each person completed 320 trials spread across five experimental blocks in a random order. The 80 shapes were shown four times each, twice in the original alignment and twice mirrored to ensure that any possible left–right biases would not systematically influence people's directional judgments. Each shape was followed by two peripheral disks with a 150-ms or 300-ms SOA (80 shapes $\times$ 2 alignments $\times$ 2 SOAs).

Procedure. The behavioral task from Experiment 2 can be seen in Figure 4. People were asked to look to the center of the screen at the start of each trial. A white shape (diameter approximately 4°) appeared on a black background in the center of the screen followed by the onset of two gray disks (diameter 2°), one on the left and the other on the right side of the screen (8° eccentricity). The shape and the disks stayed on the screen until the person responded.

Participants held a button box with both hands. They were instructed to push the left button if they thought a shape pointed or directed them to the left dot, and push the right button if they thought a shape pointed or directed them to the right dot. They were told to respond as soon as the dots appeared and were informed that there were no correct or incorrect responses for any of the shapes. Each person completed a short practice session with separate shapes.

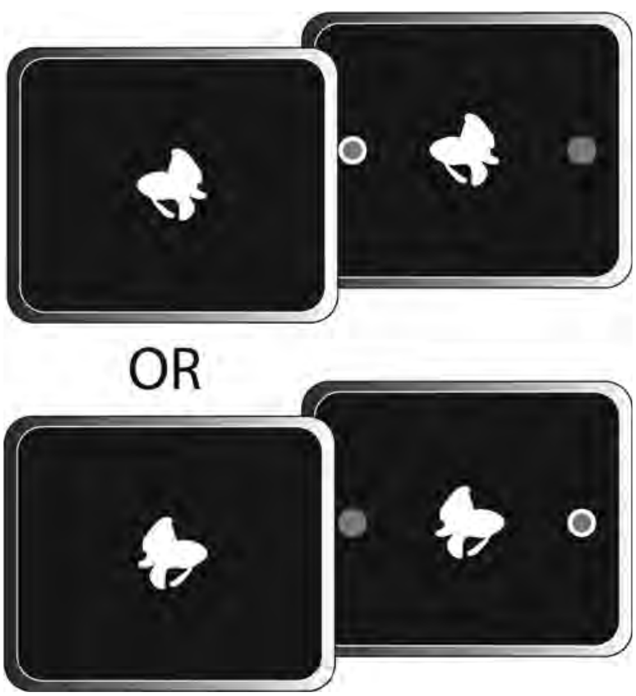

Figure 4. Task in Experiments 2 and 3. In Experiment 2, a central shape was shown, followed by the appearance of two peripheral disks. Participants indicated whether the shape pointed or directed them to the left or right disk by pressing one of two response buttons. These judgments were used as indicators of each shape's directionality. In Experiment 3, a shape was followed by the display of only a single disk that could appear with equal likelihood in a direction congruent or incongruent with the shape's inherent directionality. Participants indicated which side of the screen the disk appeared on by pressing the appropriate button. An example congruent disk is marked here with a white circle; no white circles were shown in the actual experiments.

Results

For each SOA (150 ms and 300 ms), we calculated a measure of a shape's directionality. We did so by determining whether a shape and its mirror image were reported to have opposite directionality. If they did, the participant was said to have determined that a shape had a particular directionality, which we arbitrarily call positive and negative (positive: original shape pointed left, mirror image right; negative: vice versa). We then counted the number of participants who indicated that a particular shape had a positive directionality, subtracted the number of participants who reported that the shape had a negative directionality, and divided the difference by the total number of participants. This measure of directionality can theoretically range from -1 (all participants indicate a negative directionality) to 1 (all participants indicate a positive directionality).

As can be seen in Figure 5, there is a high correlation between the directionality of the shapes at the two SOAs, $r(78) = .91$, $p = 3.9 \times 10^{-32}$, and the regression line passes through the origin (y-intercept is not statistically different from 0; $p = .475$). Therefore, a shape's directionality appears to be unaffected by the time of probing. The high correlation between the two measures indicates that they are capturing the same construct (i.e., directionality) with some added noise. We therefore combined the measures by taking their average. The measure's sign was used in all following experiments as a binary statistic indicating each shape's directionality; that is, was a shape deemed to be leftward or rightward in its original position? The measure's absolute value was used in a cross-experiments analysis as an indicator of directionality strength or consensus (see Individual Item Analysis). A two-factor analysis of variance (ANOVA) with directionality strength as a dependent measure did not reveal any significant effects of either the complexity of the shapes (whether their polygons were made by fitting a spline to eight or 16 coordinates) or whether they were symmetric or asymmetric: main effect of complexity, $F(1, 76) = 2.860$, $p = .095$; main effect of symmetry, $F(1, 76) = 1.730$, $p = .192$; interaction, $F(1, 76) = 0.022$, $p = .882$.

Experiment 3: Shape-Induced Covert Visual Orienting of Attention

Our claim is that the capability of biasing orienting is a general property of shape, even without explicit training or learning, instead of being limited to a select few overlearned objects. In Experiment 3, we therefore used several novel shapes and asked whether they automatically pushed visual attention in a particular direction. We would reach this conclusion if people were faster at detecting visual targets when novel shapes pointed to their location even though targets were no more likely to appear there than they were to appear in the opposite direction. We additionally wanted to see whether these effects were time sensitive. We expected the shape of the objects to rapidly and automatically lead to the formation of an initial hypothesis of where to pay attention, soon to be rejected because relying on the shapes' directionality was maladaptive for performance in the task. We therefore expected a rapid waxing and waning of the effects of shape-derived directionality on the allocation of spatial attention akin to the time course of

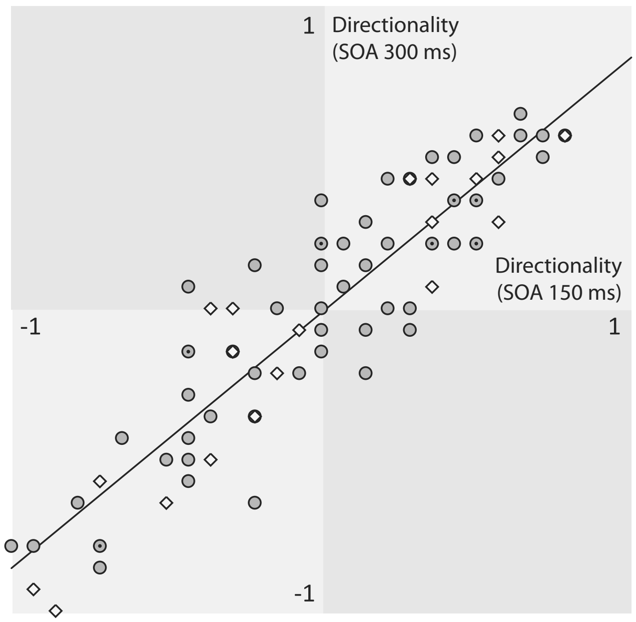

Figure 5. Directionality of novel shapes. Each novel shape's directionality is indicated by a marker. Symmetrical shapes are marked with a light gray diamond, and asymmetrical shapes with a dark gray circle. A diamond embedded in a circle is a marker for two shapes, one symmetrical and the other asymmetrical. A circle marked with a dot represents two asymmetrical shapes. Directionality can theoretically range from −1 (everyone judges a shape to have negative directionality) to 1 (everyone judges a shape to have positive directionality). Directionality judgments were highly similar at two stimulus onset asynchronies (SOAs). For details, see Experiment 2: Forced Choice of Directionality.

transient visual attention (see, e.g., Nakayama & Mackeben, 1989).

Method

Participants. Participants were 20 people (12 women, eight men), ages 18–28 ($M = 21$).

Stimuli. Forty out of 80 shapes used in Experiment 2 were used as stimuli in Experiment 3. The shapes with the strongest directionality, as determined by responses in Experiment 2, were used with the constraints that the proportions of shape types (symmetric or asymmetric, generated from eight or 16 coordinate polygons) were the same as in the original shape set. Stimuli were displayed as described for Experiment 2.

Design. Each person completed 960 trials in a random order. The trials were spread over 10 blocks and were completed in a single day. Each shape was shown equally often in its original alignment and mirrored (see Experiment 2). A disk target followed the shape onset with an SOA of 0 ms, 50 ms, 100 ms, 150 ms, 300 ms, or 500 ms. The design was fully crossed (40 shapes × 2 polarities × 2 disk locations × 6 SOAs) so that the shapes predicted neither where nor when a target would appear.

Procedure. Eye position was monitored with an EyeLink 1000 eye tracker (SR Research). Participants had to maintain fixation within 0.65° of the center throughout each experimental trial, otherwise it would abort. Participants held a response button box with both hands. A shape was displayed in the center. A single gray disk target (diameter 2°) appeared with a variable time delay on the horizontal meridian, either on the left or the right side of the screen at an eccentricity of 8°. Shapes did not predict either where or when a target would appear. The task is depicted in Figure 4.

People were instructed to press the left button if this target appeared on the left and press the right button if it appeared on the right. They were asked to do this as fast as they could while keeping their responses nearly 100% correct. Before data collection began, participants completed a short practice session with a circular shape.

It should be noted that data from a secondary task were collected from participants in Experiment 3. This secondary task was a replication of Experiment 2 except that the SOA was fixed at 150 ms. Before their main session (procedure described above), participants judged the directionality of those 40 out of the original 80 shapes that were not used as stimuli in Experiment 3. After their main session, participants judged the directionality of the 40 remaining shapes that were used as stimuli in Experiment 3. The data from the secondary task were not used since responses in Experiment 3 could be sufficiently predicted based on data collected from an independent group of people who participated in Experiment 2, as described in the Results section.

Results

Overall accuracy ranged from 92% to 100%. Accuracy was slightly, but significantly, greater on congruent ($M = 98.2\%$) than incongruent trials ($M = 97.7\%$), (paired-samples t test) $t(19) = 2.301$, $p = .033$, $d = 0.51$. A trial was considered congruent if a central shape pointed in the direction of a peripheral target, as determined by an independent sample of participants in Experiment 2, and incongruent if the shape pointed in the opposite direction. We looked at effects on response times for correct trials only.

Thirteen people completed all 960 trials with full eye tracking. Seven people either did not complete all trials or completed all trials but we were unable to track their eyes for the whole duration of the experiment. The results for these two groups were qualitatively similar, and similar conclusions would be drawn from statistical analysis on their data (see the supplemental materials, Figure 3). We therefore included data from all participants in an ANOVA with response time as a dependent measure and two repeated factors, congruency and SOA (the time between the onset of the shape and the target). Response time was considered to be the time between target onset and manual response.

People were significantly faster when the shapes' directionality was congruent with the target location (see Figure 6), $F(1, 19) = 22.159$, $p = 1.5 \times 10^{-4}$, $\eta_p^2 = .54$. The mean response time also decreased as more time passed between the onset of the shape and the target, $F(1.76, 33.40) = 75.91$, $p = 4.5 \times 10^{-13}$, $\eta_p^2 = .80$. The interaction between congruency and SOA was only marginally significant, $F(5, 95) = 1.967$, $p = .090$. Joint tests of the effects of congruency within each level of SOA showed that 50 ms was the earliest SOA at which congruency had a significant effect on response time, $F(1, 95) = 21.32$, $p = 1.5 \times 10^{-5}$ (Bonferroni corrected threshold for significance: 0.008, $d = 0.99$).

All participants in Experiment 3 were right-handed. It is conceivable that congruency effects were mainly driven by trials when

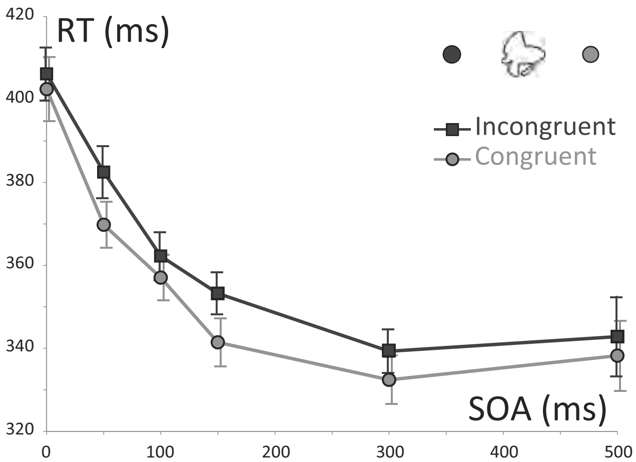

Figure 6. Shape-induced orienting of attention. Mean response times (RTs) from Experiment 3 are shown as a function of stimulus onset asynchrony (SOA) and whether the location of a target was congruent (light gray) or incongruent (dark gray) with the inherent directionality of a nonpredictive central shape cue.

the target was on the right and the participants thus responded with their dominant hand. Using only correct trials, we therefore performed another ANOVA with response time as a dependent measure and three repeated factors: congruency, SOA, and target position (on the left or right). The main effects of congruency, $F(1, 19) = 21.25$, $p = 1.9 \times 10^{-4}$, $\eta_p^2 = .53$; SOA, $F(1.71, 32.44) = 76.60$, $p = 4.0 \times 10^{-13}$, $\eta_p^2 = .80$; and target position, $F(1, 19) = 5.26$, $p = .033$, $\eta_p^2 = .22$, were all significant, as was the interaction between SOA and target location, $F(3.10, 58.89) = 6.44$, $p = 3.4 \times 10^{-5}$, $\eta_p^2 = .25$. People were faster on congruent trials, they got faster as SOA increased, they were faster for left than for right targets, and this difference for left and right targets decreased with longer SOAs. There was, however, no significant interaction between congruency and target location, $F(1, 19) = 0.04$, $p = .85$, nor a significant three-way interaction of congruency, SOA, and target location, $F(5, 95) = 1.03$, $p = .41$. The congruency effect does therefore not appear to depend on the target's position or the hand used to report it.

Interestingly, there was enough variability explained by target location that when it was included as a factor in the ANOVA, a significant interaction between congruency and SOA was revealed, $F(5, 95) = 2.41$, $p = .042$, $\eta_p^2 = .11$. The dependency of the congruency effect on SOA was close to but not exactly as expected. We had hypothesized that the congruency effects would have a sharp monotonous increase followed by a decrease. Instead, the congruency effects appeared to peak twice, once at the 50-ms SOA and again at the 150-ms SOA. Although surprising, two peaks at approximately those same time points have been reported before for transient visual attention (see, e.g., Nakayama & Mackeben, 1989, Figure 7). We will leave it to future studies to find out whether there might be two processes underlying the effects we see here.

In summary, people in general are both faster and more accurate at detecting a single target if its location is congruent with the directionality of a nonpredictive central shape cue. The congruency effects vary with SOA and are apparent very early on, as early as 50 ms after visual onset of a shape.

Experiment 4: Overcoming Shape-Induced Biases

Experiment 3 showed that the shape of an object rapidly and automatically pushes covert attention in a particular direction. How easily can this bias be overcome? Experiment 3 was deliberately set up to have no cue–target contingencies, making the shape useless with regard to the participants' detection task. In Experiment 4, all shapes provided accurate information about the location of an upcoming target. However, some cue–target contingencies were in accordance with the shape's directionality, whereas others conflicted with it. Would experience with these cue–target contingencies make people overcome their initial shape-induced biases?

We designed a task where a target always appeared in the location to which some shapes pointed, whereas for other shapes it always appeared in the location that they pointed away from. If people are consistently faster at finding the target in the former case than in the latter, even though all shape cues are informative, we would conclude that a shape's directionality not only influences behavior in a situation when there is nothing else to go on, but also comes into play even when other, more accurate information is available.

Method

Participants. Sixteen people (six women, 10 men) between the ages of 18 and 30 ($M = 22$) participated.

Stimuli. Eight simple asymmetric shapes were used as central precues in a visual search task. The shapes were black, had the same area, and had an approximate diameter of 3°. The shapes' directionality had been determined in Experiment 2.

People searched for a target cross among distractor plus signs. Distractors were made by overlaying a vertical and a horizontal bar (1.1° × 0.3° each). The target was made in the same way except that one bar was vertically displaced by 0.2°. The search stimuli were then given a random rotation on each trial. The search stimuli were black, except that a small colored circle (diameter 0.1°) was embedded in each of them. The target's circle color could be red or green and was chosen at random. The color of each distractor's circle was also randomly determined to be red or green with the constraint that there was at least one distractor disk of each color.

Design. Two sets of four shapes were used in this experiment. Half of the participants were given one set, and half were given the other set. Each shape served as a predictive central precue in a visual search task. It cued one of four possible target locations (upper left, upper right, bottom left, or bottom right).

Two shapes were congruent, meaning that the shapes' inherent directionality was consistent with the direction of the target location that it cued. The other two were incongruent; they cued a target location in a direction opposite to that of their inherent directionality. The two congruent shapes cued target locations on one diagonal, and the two incongruent shapes cued target locations on the other diagonal (see Figure 7). The rotation of each shape was the same across all participants with the same shape set, but the cue–target contingencies differed; each shape served as a congruent cue for four participants and as an incongruent cue for another four participants.

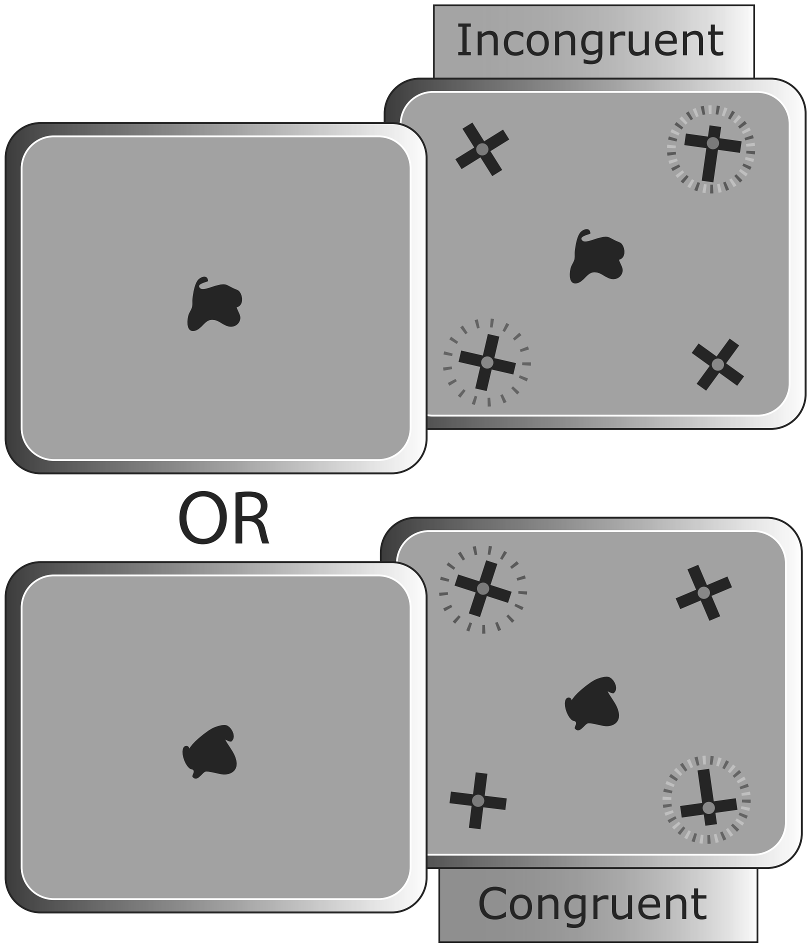

Figure 7. Task in Experiment 4. A central shape validly cued the location of a peripheral target cross shown among distractor plus signs. Participants had to find the cross and report its central color. Although all shapes provided accurate information about the upcoming target location, the cued location was congruent with the directionality of half of the shapes but incongruent for the other half. Examples of congruent and incongruent search trials are shown. Cued locations are indicated by yellow dotted circles. The locations pointed to and away from are indicated by blue and red dotted circles, respectively. No dotted circles were actually shown to the participants.

Central shape cues therefore predicted, with 100% accuracy, where peripheral targets would appear. The correctly predicted location could be congruent or incongruent with the shape's inherent directionality. Each participant completed 240 search trials spread over four blocks during a single session.

Procedure. Eye position was monitored with an EyeLink 1000 eye tracker (SR Research). The participant's gaze on a central 0.3° × 0.3° fixation square triggered the start of each search trial; the participant was then free to move her or his eyes for the remainder of the trial. The fixation square was replaced by a predictive central shape cue that was visible throughout the trial. The participant was told that a shape would appear on the screen after she or he had acquired fixation, and that after the shape appeared a search array would show up on the screen. After 500 ms, a square search array with three distractors and one target appeared around the central shape. The search stimuli were all shown at 11° eccentricity. The participant had to find the target and report the color (red or green) of an embedded disk by pushing the button of the corresponding color on the response box. This completely disambiguated the manual response from the directionality of the shape. The procedure is depicted in Figure 7.

Participants were instructed to respond quickly but to try to maintain near perfect performance. Auditory feedback was given to indicate whether a response was correct or incorrect.

Results

Mean accuracy ranged from 92% to 98%. People were significantly more accurate at judging the color of a disk embedded in a target if the target was preceded by a shape cue whose directionality was congruent (M = 96.2%) rather than incongruent (M = 94.8%) with the target's location, (paired-samples t test) $t(15) = 3.257$, $p = .005$, $d = 0.81$. Error trials were not further analyzed.

Mean response time was used as a dependent measure in a repeated measures ANOVA with block (one to four) and congruency as factors (see Figure 8). The main effects of block, $F(3, 45) = 9.57$, $p = 5.3 \times 10^{-5}$, $\eta_p^2 = .39$, and congruency, $F(1, 15) = 15.05$, $p = .001$, $\eta_p^2 = .50$, were significant, but the interaction between the two factors was not significant, $F(3, 45) = 0.98$, $p = .409$. Overall, response times decreased over the course of the experiment. Participants were also faster at reporting the attributes of a peripheral target when it was in a location congruent with a central shape cue's directionality. This effect did not seem to diminish over the course of the experiment.

Because congruent and incongruent shapes were equally predictive of where a target would appear, one might have expected that the performance gap between congruent and incongruent shapes would narrow as people gained more experience with the cue–target contingencies. Although this might potentially happen with longer training, we saw no sign of it, and the benefit for congruent shape cues persisted. It thus appears that people intuitively make certain associations more easily than others and that this preference is not easily erased in a single session.

Experiment 5: Shape as a Movement Cue

So far we have shown that the shape of an object is used to rapidly and automatically extract its directionality, and that this in turn guides both overt and covert visual orienting. An unanswered question is why the visual system is set up this way at all. One possible reason is that the shape of an object restricts and thus predicts its movements. A snapshot of the shape of an object might therefore provide valuable information about where it may be moments later. The rules governing selective sampling of the environment should incorporate any available data, including shape, which provides prior information about where important things are going to be in the near future. Informal self-reports of participants in Experiments 1 and 2 also indicated that judgments about the directionality of shapes could be related to people's perceptions about where the things were moving or heading. In Experiment 5, we directly examined whether the shape-defined directionality of an object was integrated into calculations about its movement. We would reach this conclusion if people were consistently faster at judging where an object was heading if its direction of motion was congruent with the directionality derived from the object's shape.

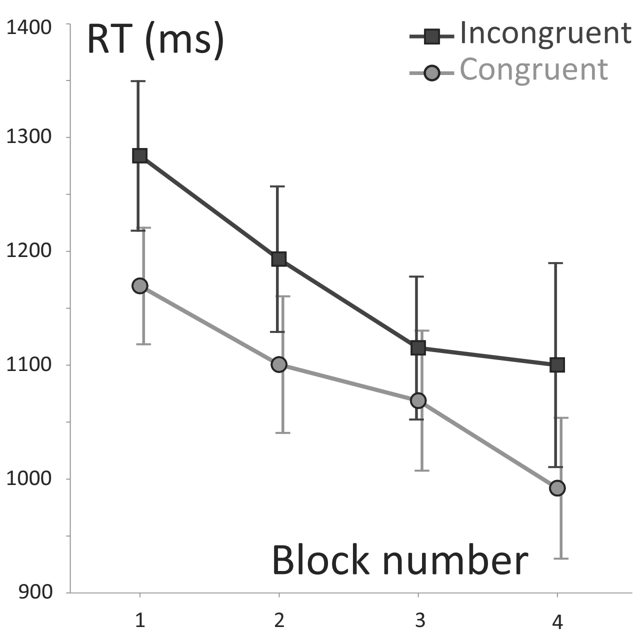

Figure 8. Congruency effects over the course of learning. Mean response times (RTs) are shown for experimental blocks in Experiment 4. A central shape cue predicted, with 100% accuracy, where a peripheral target would appear. The correctly predicted location could be congruent (light gray) or incongruent (dark gray) with the shape's inherent directionality.

Method

Participants. Sixteen people (seven women, nine men) of ages 18–54 ($M = 27$) participated in the experiment.

Stimuli. Stimuli were the same 40 shapes used in Experiment 3. The shapes were white and shown on a black background. Each shape extended approximately 1°.

Design. Each person completed 320 experimental trials in two blocks within a single session. All shapes were shown four times within each block in a random order (40 shapes $\times$ 2 shape directionalities $\times$ 2 movement directions $\times$ 2 repetitions).

Procedure. The participant was instructed to look at a fixation disk (white 0.5° diameter) at the beginning of each trial. The participant was otherwise free to move her or his eyes. The fixation disk stayed on-screen for 510 ms, and 470 ms later participants then saw multiple copies of a particular shape lined up in a row across the screen (see Figure 9). The screen center coincided with the pivot point of the central shape (see Experiment 1). The distance between corresponding points of juxtaposed copies of the shape was 2.4°. To create a moving stimulus, the row of shapes was translated 0.8° to either the left or right every 130 ms. On any given trial, the row of shapes therefore appeared to be moving either leftward or rightward.

Shapes were shown equally often pointing to the left or the right; this directionality was defined by an independent sample of people (see Experiment 2). The shapes pointed in the direction of motion on half of the trials, and pointed the opposite way on half of the trials. Shape was not a valid predictor of motion.

Participants held a response button box with both hands and were told to press the left button if the shapes were moving to the left and press the right button if they were moving to the right. A tone sounded when the participant responded. No specific feedback was provided about whether the answer was correct or incorrect.

Results

Mean accuracy ranged from 89% to 99%. Although accuracy was generally very high, people were significantly more accurate at judging where the shapes were going when the shapes pointed in the direction to which they were moving (congruent: $M = 97.9\%$; incongruent: $M = 95.0\%$), (paired-samples t test) $t(15) = 4.408$, $p = .001$, $d = 1.10$.

We calculated the mean response times for correct trials only. Response times were defined with respect to motion onset, which was the time of the first translation of the multishape stimulus. All participants were faster at judging where the shapes were going if their movement direction was congruent with their inherent directionality (see Figure 10). This effect was significant (congruent: M = 317 ms; incongruent: M = 353 ms), (paired-samples t test) $t(15) = 9.746$, $p = 7.0 \times 10^{-8}$, $d = 2.44$.

Experiment 6: Match to Motion

The results from Experiment 5 were quite robust; every participant was faster at judging where a shape was going if it pointed in the direction of motion. We interpret this as evidence for the idea that the shape of an object, in particular its shape-derived directionality, is automatically integrated into movement calculations.

In Experiment 6, we wanted to address two alternative interpretations. First, we wanted to rule out the possibility that any slight pixel-by-pixel differences between leftward and rightward shapes solely determined an object's supposed directionality and its behavioral effects. Secondly, it is possible that we were not seeing an effect on motion perception but rather a type of effector priming; certain shape features might afford being grasped by a particular hand, and a button press with that hand might thus become potentiated. The stimuli in Experiment 5 were all very small two-dimensional silhouettes that, if perceived as graspable at all, probably all afforded a similar pincer grip; nonetheless, we wanted to rule out this explanation.

To address these possibilities, we designed an experiment where moving shapes had a random starting position, and where manual responses were directly related neither to the direction of motion nor to the directionality of shapes. If people are still faster at judging the direction of motion of an object when it is congruent with the directionality derived from its shape, we would conclude that these alternative interpretations do not sufficiently account for our effects and that, instead, shape-derived directionality is integrated into the calculations of an object's motion path.

Method

Participants. Sixteen people (eight women, eight men) of ages 18–34 (M = 22) took part in this experiment. One additional participant was excluded because of very low accuracy rate (more than 6 standard deviations below the mean).

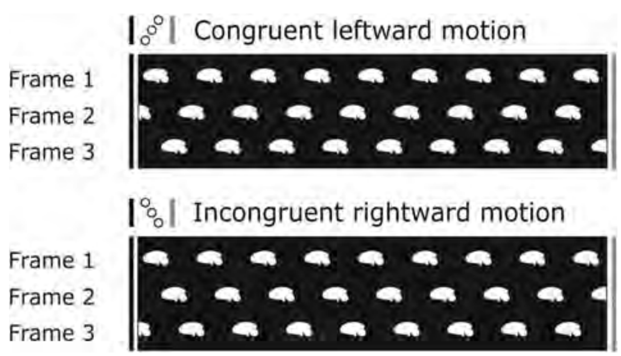

Figure 9. Example motion stimuli. To create a moving stimulus in Experiments 5–7, a row of shapes was translated in a direction that was either congruent or incongruent with the shapes' inherent directionality. The direction to which the example shapes are most often judged to point is indicated by a black vertical bar, and the opposite direction is indicated by a gray vertical bar.

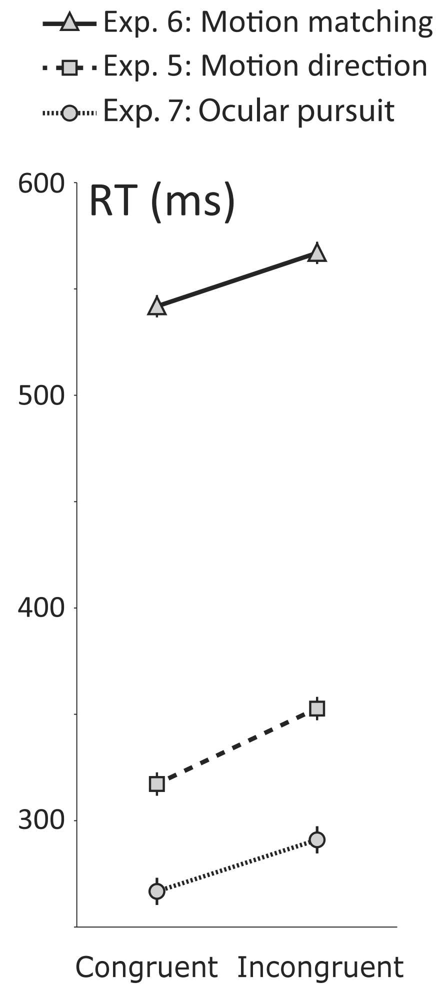

Figure 10. Shape as a movement cue. Mean response times (RTs) are shown as a function of congruency between shape-derived directionality and direction of motion. When an object moved in the direction to which it pointed, people were faster at judging its direction of motion (Experiment 5: Motion direction, course dotted line with squares), matching its motion to the motion of other objects (Experiment 6: Motion matching, solid line with triangles), and following it with their eyes (Experiment 7: Ocular pursuit, fine dotted line with circles). Note that confidence intervals are small.

Stimuli. Shape stimuli were as described for Experiment 5 with the addition of a white disk shape (diameter 0.9°).

Design. Participants completed 320 trials each in four blocks within one session. Trials were shown in a pseudorandom order. The design was fully crossed (40 shapes × 2 polarities × 2 shape movement directions × 2 disk movement directions).

Procedure. Procedure was as described for Experiment 5 with the following changes. Presentation of a central fixation spot was followed by the appearance of several disk shapes that extended to the screen's edges. The horizontal starting position of the disks was random, but the distance between the centers of adjacent disks was fixed at 2.4°. All disk shapes were translated 0.8° degrees every 130 ms so that they appeared to move either leftward or rightward. The disks disappeared 390 ms after their initial onset. After a 500-ms interstimulus interval, participants saw multiple copies of a particular novel shape. Their horizontal starting position was random, but the distance between corresponding points on two adjacent shapes was always 2.4°. The shapes could point leftward or rightward, and could move leftward or rightward, as detailed in Experiment 5 (see also Figure 9).

Participants indicated whether each novel shape was moving in the same direction as the disks (match) or in a direction opposite that of the disks (nonmatch). Participants responded with their right hand using a two-button box. The button box was aligned so that one button was nearer the person and the other was farther away. Half of the participants pushed the closer button to indicate a match and the button farther away to indicate a nonmatch, and vice versa for the other half of the participants. Participants completed some practice trials with other shapes randomly picked from the rest of the original shape data set used in Experiment 2.

Results

Mean accuracy ranged from 84% to 100%. Participants were on average more accurate on trials where the shape's directionality was congruent with the shape's own direction of motion; this difference did not reach statistical significance (congruent: M = 95.6%; incongruent: M = 94.1%), (paired-samples t test) $t(15) = 1.676$, $p = .114$. Error trials were not analyzed further.

Response times were defined as the time between the novel objects' motion onset and button press. People were significantly faster when novel shapes pointed in the direction to which they were moving (congruent: M = 542 ms; incongruent: M = 567 ms), (paired-samples t test) $t(15) = 7.244$, $p = 3 \times 10^{-6}$, $d = 1.81$ (see Figure 10).

We regressed the objects' starting position against response time. By *starting position* we refer to the location of the pivot point (see Experiment 1) of the central shape in the first frame *relative* to the direction of motion; for example, if the pivot is 1° to the right of the screen center but the shape is moving leftward, then the shape's starting position is considered to be −1° relative to the motion direction. For each participant, we calculated the slope of the best fitting line (least squares method) and did so separately for congruent and incongruent trials. The participants' mean slopes for congruent (M = 0 ms) and incongruent trials (M = 7 ms) were neither significantly different from 0, (single-sample t test, congruent trials) $t(15) = 0.116$, $p = .909$; (incongruent trials) $t(15) = 1.561$, $p = .139$, nor significantly different from each other, (paired-samples t test) $t(15) = 0.977$, $p = .344$. Starting position was not found to be a significant factor contributing to response times in this task.

People are therefore faster at judging the direction of movement of an object if its shape is congruent with the object's motion path. This cannot be attributed solely to pixel-by-pixel differences between leftward- and rightward-pointing objects because their starting position was randomly varied. The effect cannot be attributed to effector priming either; the effect was found even though people used one hand only and the button presses were orthogonal to the objects' direction of motion and shape-derived directionality.

Experiment 7: Shape Effects in Oculomotor Programming

Experiments 5 and 6 showed that shape can play a significant role in motion perception. However, we are especially interested in the contribution that shape information can make to action guidance, in particular oculomotor guidance, considering that shape selectivity has been found in important oculomotor centers of the brain (Janssen et al., 2008; Konen & Kastner, 2008; Lehky & Sereno, 2007; Peng, Sereno, Silva, Lehky, & Sereno, 2008; A. B. Sereno & Maunsell, 1998; M. E. Sereno et al., 2002). Given the numerous dissociations between perception and action (Goodale, 2008; Goodale & Milner, 1992; Milner & Goodale, 1995, 2010), including oculomotor behavior (Mack, Fendrich, Chambers, & Heuer, 1985; Spering & Gegenfurtner, 2008; Spering & Montagnini, 2011; Wong & Mack, 1981), we thought it important to test whether shape affects the programming of eye movements in addition to perception. Additionally, we wished to compare the effects of novel random shapes with those of arrows, which are both familiar and highly directional, and with filled circles, which should be adirectional, to see whether shape-derived directionality mainly helps or hinders performance relative to situations in which no bias should be present. People were asked to follow a row of moving shapes with their eyes. They were free to use both saccadic and smooth eye movements for this ocular pursuit task. We expected eye movements in the direction to which the shapes were pointing to be facilitated, and eye movements in the opposite direction to be hindered.

Method

Participants. Sixteen people participated (seven women, nine men). Their ages ranged from 18 to 24 years (M = 21).

Stimuli. We used 40 novel shapes, as described for Experiment 5, and four additional shapes: three differently shaped arrows and a filled circle. All shapes, including the arrows and the circle, had the same area and an approximate diameter of 1°.

Design. Each person completed two experimental blocks for a total of 184 trials in random order. All directional shapes (40 novel shapes, 3 arrows) were shown four times each (2 motion directions × 2 shape directionalities). Circular shapes were shown on control trials (2 motion directions × 3 repetitions).

Procedure. The experimental procedure was as described for Experiment 5 (see also Figure 9) with the following changes. At the beginning of each trial, the screen center always coincided with the center of area of the central shape in each multishape stimulus. People were told to follow the shapes' movement (leftward or rightward) with their eyes. Eye position was tracked; a trial started once a person had acquired fixation on a central fixation spot. Instead of responding to the direction of motion with a button press, the trial ended once people's eyes reached one of two invisible circular regions: a target region in the direction of motion (correct response) or a distractor region in a direction opposite that of the real motion of the shapes (incorrect response). The circular regions were centered on the horizontal meridian at 6.0° eccentricity with a radius of 3.0°. Trials were considered valid if the participants' horizontal eye position within the first 130 ms after stimulus onset was no further than 0.65° from the screen's center, and vertical eye position was no further than 1.0° from the horizontal meridian throughout the trial. Furthermore, trials were considered valid only if people reached one of the circular regions within 2,000 ms of motion onset. On average, 79.2% of trials were deemed valid, and we base our analysis on these valid trials only.

Results

Participants' mean accuracy for novel shapes ranged from 62% to 100%. This great range of performance was surprising, since the task was mainly designed to measure response time and not accuracy levels. Accordingly, here we saw a much greater difference between the accuracy in congruent (M = 92.9%) and incongruent (M = 84.2%) novel shape trials than in our previous experiments where accuracy was closer to ceiling. People were significantly more accurate on congruent than incongruent novel shape trials, (paired-samples t test) $t(15) = 3.865$, $p = .002$, $d = 0.97$). Response times were calculated relative to motion onset on correct trials only. People were significantly faster at reaching the target region, located in the direction of motion, if the novel shapes' inherent directionality was congruent with the direction of motion (congruent: M = 267 ms; incongruent: M = 291 ms), (paired-samples t test) $t(15) = 5.719$, $p = 4.1 \times 10^{-5}$, $d = 1.43$ (see Figure 10). We note that the effect of congruency on both accuracy and response time remains significant even when invalid trials are included in the analysis.

We compared the effects of novel shapes with the effects of arrows. People were far more accurate when the arrows pointed in the direction of motion than if they pointed in the opposite direction (congruent: M = 100.0%; incongruent: M = 53.0%), (paired-samples t test) $t(15) = 9.918$, $p = 5.6 \times 10^{-8}$, $d = 2.48$, and almost twice as fast (congruent: M = 240 ms; incongruent: M = 405 ms), (paired-samples t test) $t(14) = 5.231$, $p = 1.3 \times 10^{-4}$, $d = 1.35$ (one person had no correct incongruent trials and was therefore not included in the response time measures). People were also significantly faster and more accurate for congruent arrows than they were for congruent novel shapes, and they were significantly slower and less accurate for incongruent arrows than they were for incongruent novel shapes (paired-samples t tests, all ps $<$ .003, all ds $>$ 0.96). As expected, arrows are therefore particularly effective stimuli for orienting guidance.

Finally, we compared novel shapes to filled circles (which have no directionality). The mean accuracy (M = 88.9%) and response times (278 ms) for circles fell halfway in between those of congruent and incongruent novel shapes. The differences in accuracy for circles and congruent shapes were not reliably smaller or larger than the differences in accuracy for circles and incongruent shapes, $t(15) = 0.221$, $p = .828$. Response time differences for circles and congruent shapes were not reliably smaller or larger than those for circles and incongruent shapes, $t(15) = 0.129$, $p = .899$. The effects of directionality therefore appear to be more or less symmetrical; the more congruent a shape's directionality is with the direction of motion, the faster and more accurate the oculomotor behavior, and the more incongruent a shape's directionality, the slower and more error prone is the behavior. Shape-derived directionality appears to be a strong enough motion cue that the stimuli can be perceived to move, and are thus initially pursued, in the direction opposite that of the "real" motion. Overall, our results support the hypothesis that novel shapes have an automatic effect on oculomotor programming.

Individual Item Analysis

The possibility remained that our results were driven only by a few atypical novel shapes, with the rest of them contributing nothing to the effects. For example, it was possible that by random chance, a few of our shapes looked like arrows and that these atypical shapes were the sole driving force behind our results. To rule out this possibility, we analyzed congruency effects for individual shapes. We did so with data collected for novel shapes in Experiment 3 (detection), Experiment 5 (motion direction), Experiment 6 (motion matching), and Experiment 7 (ocular pursuit). For Experiments 3, 5, and 6, we calculated the mean response time on incongruent and congruent trials for each shape for each participant, calculated response time savings by subtracting the former from the latter, and finally found the mean response time savings for each shape across participants within a particular experiment. We included all trials regardless of people's responses to get adequate sampling of responses to each shape. Data from one participant in Experiment 3 was excluded because she did not complete both congruent and incongruent trials for all of the shapes. For Experiment 7, most participants had at least one shape with either no valid congruent trials or no valid incongruent trials; we therefore collapsed across participants and calculated mean response times savings for each novel shape. Collapsing across participants allowed us to include only correct trials for response time calculations and still retain enough trials for each of the novel shapes. Accuracy had a much greater range in Experiment 7 than in our other experiments, providing us with the opportunity of also looking at accuracy savings found by subtracting the percent of correct incongruent trials from the percent of correct congruent trials for each novel shape.

Results

The response time savings for the 40 novel shapes were positively correlated across all four tasks (see Figure 11). Accuracy savings in the ocular pursuit task (Experiment 7) were also positively correlated with response time savings from all four tasks (Figure 11). Assuming that any one measure is a somewhat noisy estimate of the same construct, that is, the strength of a shape-derived directional bias, we combined all five measures into a single measure of an overall congruency advantage. We did so by dividing each original savings measure by its standard deviation and then took the average for each shape across the five scaled measures.

The five original measures of savings were positively correlated with directionality strength as defined by the degree of consensus reached on the directionality of shapes in Experiment 2 (see Figure 11). The overall congruency advantage scores were also significantly correlated with directionality strength, $r(38) = .489$, $p = .001$. As can be seen in Figure 12, the behavioral effects were not due to a few outlier shapes; instead they were graded and related to the shapes' directionality strength. Regressing directionality strength against the congruency measure also revealed that the y-intercept (congruency advantage: -0.260) was not significantly different from 0 (p = .423), indicating, unsurprisingly but reassuringly, that an adirectional shape would be expected to induce no directional behavioral bias.

The analysis of individual novel shapes shows that the stronger the directionality of a shape, the greater its behavioral biasing

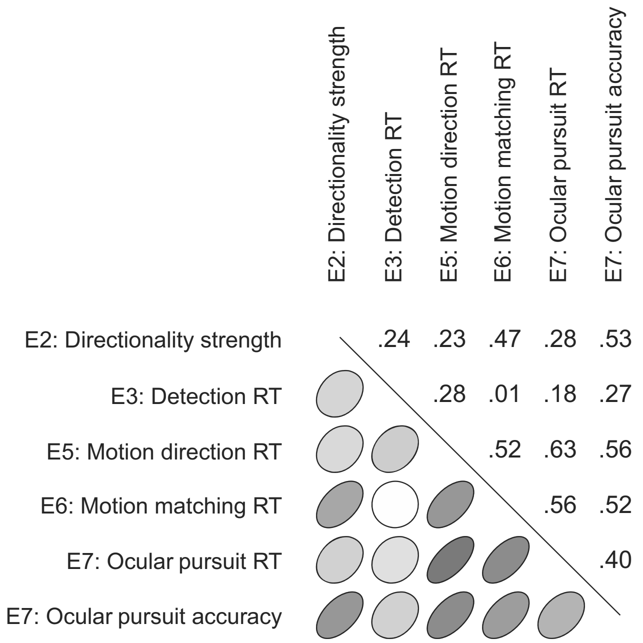

Figure 11. Congruency effect correlation matrix. This matrix shows the relationship between directionality strength (Experiment 2) and savings measures from various tasks (Experiments 3, 5, 6, and 7, summarized in Individual Item Analysis). Numbers indicate Pearson's *r*. Ellipses are the contours of a bivariate normal distribution with a correlation *r* (Murdoch & Chow, 1996). E = experiment; RT = response time.

effects will, in general, be. This analysis also shows that our results were not driven by few very atypical shapes. Instead, congruency effects were found for a great number of shapes across various tasks. We find it parsimonious to conclude that the effects are not solely explained by resemblance to specialized stimuli such as arrows, but that the visual system instead automatically assigns directionality to many different shapes, and that this drives or biases further visual processing and guides behavior.

General Discussion

We hypothesized that the visual system uses information about shape to swiftly and automatically extract the directionality of virtually any object without explicit training or learning. We explored this idea in several related experiments. A majority of randomly generated novel shapes were reliably judged to have one or more main directions (Experiments 1 and 2). This inherent shape-derived directionality was found to automatically guide both overt (Experiment 3) and covert (Experiments 4 and 7) visual orienting of attention. The effect was rapid (Experiment 3), resistant to experience (Experiment 4), and integrated into the assessment of an object's movement (Experiments 5–7).

Our results show that an object can rapidly and automatically push attention away from itself due to its shape. This appears to be the rule and not the exception. These biasing effects are likely to be direct instead of coming about through explicit interpretation or semantics; our objects were not symbolic, they were novel and meaningless. These orienting shifts do not need to be explicitly learned or trained. They are not easily overridden or overwritten by experience, persist even when they are not useful, and are found in various tasks and situations.

The fact that our effects arise without any particular training does not necessarily indicate that experience has no role in establishing them in the first place. Indeed, previously adirectional and nonspatial visual stimuli such as color patches can start to automatically bias covert (Dodd & Wilson, 2009) and overt (Van der Stigchel, Mills, & Dodd, 2010) visual orienting once they have often been paired with a behaviorally relevant thing or action in a particular direction. The same is true for Arabic numerals where low numbers shift overt and covert visual attention to the left while high numbers shift it to the right (Dehaene, Bossini, & Giraux, 1993; Fischer et al., 2003; Fischer, Warlop, Hill, & Fias, 2004). Although there might indeed be a true, spatial mental number line (Dehaene, Izard, Spelke, & Pica, 2008; Zorzi, Priftis, & Umiltà, 2002), the associations between directions and these particular shapes are presumably relatively arbitrary and might come about through the cultural tradition of reading from left to right, and thus shifting one's eyes and attention in the same direction (Dehaene et al., 1993; Shaki & Fischer, 2008).

The time course of learned, arbitrary visual orienting appears to be relatively slow (Fischer et al., 2003; Van der Stigchel et al., 2010) compared to the rapid effects found for novel shapes in the current study. The shape-induced biases we see arise so early that they are presumably not dependent on recurrent feedback but likely arise from an initial bottom-up sweep of visual information. The difference might be that, unlike color patches or digits, the mapping from shape to space is not arbitrary. Colors are nonspatial, and digits do not line up on any obvious spatial dimension; the shape of digits, presumably, changes completely arbitrarily going from 0 to 9. On the other hand, the directionality of a shape might lie on a dimension in a yet unknown multidimensional shape space.

Precisely documenting this shape space is beyond the scope of this article. After their participation in Experiments 1 and 2, we nonetheless asked people whether they thought they had used a particular strategy or rule to complete the tasks. We summarize these informal self-reports with the hope that it will help generate hypotheses for future experiments that parametrically vary stimulus properties to address what, exactly, determines the direction of a given shape.

Several different strategies were reported. Often people reported using some geometric properties of the shapes: direction of a large, long, tapered, or sharp protrusion, overall taper of shape; direction of the average of more than one protrusion; direction opposite a small protrusion and between two cupping protrusions; direction toward the meeting point of two tilted lines. Some reported taking into account a center of mass, like they were weighing the object, or dividing the shape into subparts and going with the direction of the part with the greatest mass or area. Some reported taking into account a general axis or an axis of symmetry. Some reported ignoring small protrusions. Some said that they had trouble judging the directionality of shapes that were blob-like or smoothly curved.

When asked, many noted that at least some of the shapes resembled real things, such as arrows, planes, or flowers, but in particular animate things such as bugs, marine life, birds, space aliens, or parts of animate things such as faces, heads, mouths, antennae, tails, legs, hands, and fingers. Some reported that they

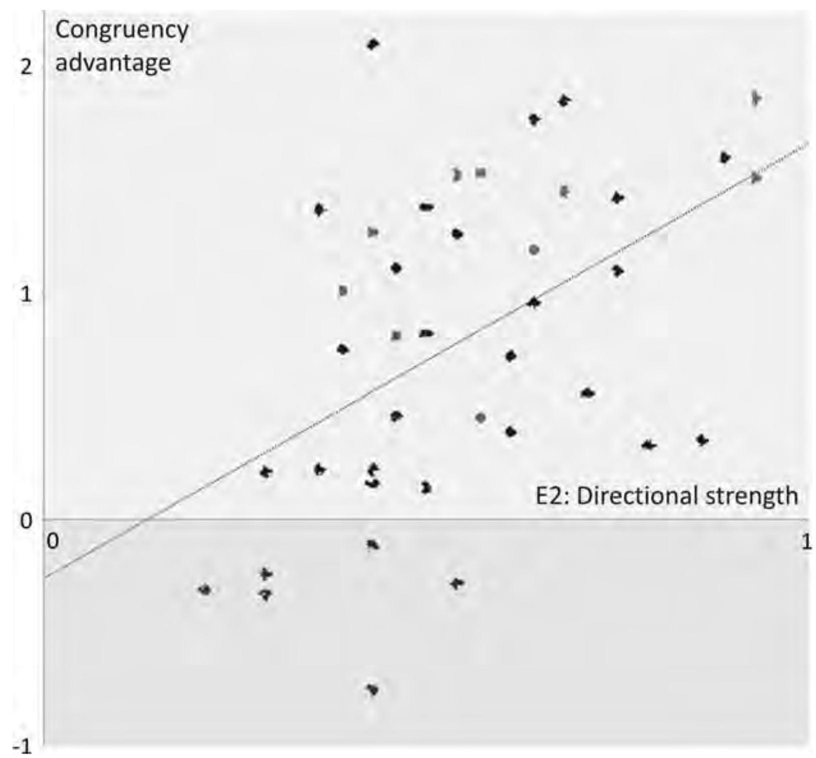

Figure 12. Behavioral effects of individual shapes. Each marker is in the shape of the corresponding novel object shown in Experiments 3, 5, 6, and 7. Asymmetric shapes are shown in black, and symmetric shapes are shown in gray. All shapes are shown pointing to the right, as judged by participants in Experiment (E) 2. Overall, the stronger the consensus is on a shape's directionality, the greater the behavioral advantage is on congruent relative to incongruent trials.

tended to go with the direction in which the shapes appeared to be moving or heading, or where they were facing, especially if the shapes appeared to be biological. Judgments of the shapes' animacy do nonetheless appear to be unrelated to the strength of their directionality; novel shapes that are deemed to look like some kind of existing or hypothetical creature, animal, or person, are not any more or less likely to have a strong directionality (H. M. Sigurdardottir, M. M. Shnayder, & D. L. Sheinberg, unpublished observations). Finally, some participants just reported that they did whatever felt right and that they were not consciously using any particular strategy.

In short, people seem to use various properties of objects to judge their directionality. Strategies span from taking into account particular features of the object's parts to using summary statistics of the whole shape to noting body structure and plausible movement patterns. The fact that people report so many different strategies or even no strategy at all suggests that several different form or shape characteristics might all come together to influence the judged directionality of an object, and that people might not necessarily have conscious access to the rules that they use to make such judgments. The algorithm used by the visual system to derive an object's directionality is therefore currently unknown, and there might be more than one mechanism at work.

We can nonetheless theorize about the mechanisms behind our results. One possibility is that our effects are driven by axis-based shape processing (see, e.g., Blum, 1967; Kimia, 2003; Lin, 1996). There is already some evidence that the visual system can use axis-based shape representations and that this affects perceptual sensitivity within an object (Hung, Carlson, & Connor, 2012; Kimia, 2003; Kovács, Fehér, & Julesz, 1998; Kovács & Julesz, 1994). In Figure 13, we have included an example shape and one scenario of how a shape's axis might affect target detectability outside its boundaries. In this example, a shape's topological skeleton is found by gradual erosion of the object's boundaries without breaking it apart (in this case using the *bwmorph* function of MATLAB's Image Processing Toolbox). The skeleton is then pruned by cutting off its smallest branches; in computer vision, regularization of a skeleton is commonly applied to reduce noise because small changes in the boundary of an object can lead to great changes in its skeleton (Shaked & Bruckstein, 1998). The visual system might explicitly assign a direction of flow along an axis segment as supposed by some axis models such as the shock map (Kimia, 2003). Through extension of the axes of the skeleton, perhaps through rules similar to those hypothesized to support collinear facilitation or contour completion (for a review, see Loffler, 2008), it is also possible that the object is grouped more strongly with targets on one side than another. For example, the association field model assumes that contours are formed by the linking of information across neighboring neural receptive fields tuned to similar orientations (Field, Hayes, & Hess, 1993; Ledgeway, Hess, & Geisler, 2005). The fact that directionality affects the perception of motion is at least consistent with the role of collinear

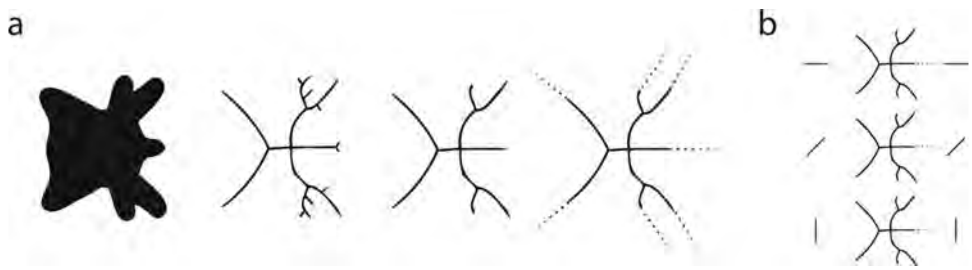

Figure 13. Hypothetical example of how a shape could affect target detectability. (A) A shape's topological skeleton is found and pruned. Through extension of the axes of the skeleton, perhaps through rules similar to those thought to support collinear facilitation or contour completion, it is possible that the shape is grouped more strongly with targets on one side than another (here more with a right than a left target). (B) This grouping might be stronger for collinear targets (top) than noncollinear targets (middle and bottom).

facilitation, since it not only may subserve contour formation but appears to influence motion perception as well; the speed of collinear sequences is overestimated (Seriès, Georges, Lorenceau, & Frégnac, 2002), and a vertical line moved horizontally toward a stationary horizontal line can be misinterpreted as the movement of the latter line, since it is parallel to the direction of motion (Metzger, 1936/2006). Real-world objects can be viewed as spatiotemporal events, and their motion can be thought of as a change in the objects' boundaries over both space and time. It might therefore be expected that mechanisms that support boundary completion in space might also be involved in boundary completion over time, where the shape of an object's current boundaries is used to predict its future state.

If mechanisms such as those underlying collinear facilitation and contour integration are involved, then a number of predictions can be made (although there is some disagreement on the relation between collinear facilitation and contour integration; see Loffler, 2008; Williams & Hess, 1998). First, the biasing effects of a shape might be expected to interact with the qualities of the target. The greatest facilitation would be expected for targets that are collinear with the directionality of the shape, and little facilitation would be expected for targets orthogonal to or tilted relative to the shape's directionality (Polat & Bonneh, 2000; Polat & Sagi, 1994). Second, there might be no congruency effects when an orthogonal distractor is placed between a target and a shape (Dresp, 1993). Third, because the detectability of a contour increases with the number of elements making up a path (Braun, 1999), a "daisy chain" of shapes could induce stronger congruency effects than a single shape; this is one possible reason why the effects in our motion paradigms (Experiments 5–7) seemed particularly robust. Fourth, the congruency effect would be expected to change in magnitude and even sign with the relative distance between the shape and the target (Polat & Sagi, 1993, 1994). Fifth, the congruency effect should reach its peak at a later time point with increased distance between the shape and the target (Cass & Spehar, 2005). It would in general be very interesting to document further how shape-induced biases develop in both space and time, where target detectability would be probed not just at several different time points but at various distances and directions from a shape.

In addition to, or instead of, the mechanisms discussed above, the rules linking shape and space might be more explicitly derived from the complex but nonrandom way in which the shape of an object restricts its movements and therefore its probable future location. Our stimuli were two-dimensional silhouettes, but real objects exist and move in a fully three-dimensional world. If an object is assigned a directionality for the purpose of predicting its future location, then real-world objects might have a directionality defined in not just two but three dimensions. If all other things are equal, an object is likely to move in a path of least resistance to air flow. Preliminary work from our laboratory suggests that directional judgments might be related to a shape's aerodynamic properties. The greater the consensus reached on the directionality of a shape, the better its path of least resistance approximated the shape's empirically defined directionality (S. Boger & S. M. Michalak, unpublished observations). Further work on the role of aerodynamics is warranted. The current results show that the visual system is able to link the appearance of an object with its possible path of motion. Directional information derived from shape can be used to guide the eyes and attention to the object's future location so that it can be tracked, examined, and acted on.

Our experiments were based on the hypothesis that the shape of an object affects the weights given to locations in a spatial priority map (Bisley & Goldberg, 2010; Fecteau & Munoz, 2006; Itti & Koch, 2001). Overt and covert visual attention would be guided to the location of peak activity within the map once activity reaches a particular threshold, and this attentional orienting signal would in turn bias other processes such as motion perception (Cavanagh, 1992; Stelmach, Herdman, & McNeil, 1994; Treue & Maunsell, 1996). Such a tight link between shape, attentional priority, and motion perception is biologically plausible; posterior parietal regions that play an important role in target selection and visual orienting (Andersen, Snyder, Batista, Buneo, & Cohen, 1998; Arcizet, Mirpour, & Bisley, 2011; Bisley & Goldberg, 2010; Colby & Goldberg, 1999; Gottlieb, Kusunoki, & Goldberg, 1998; Silver, Ress, & Heeger, 2005) are furthermore selective for the shape of objects (Janssen et al., 2008; Konen & Kastner, 2008; Lehky & Sereno, 2007; Red et al., 2012; A. B. Sereno & Amador, 2006; A. B. Sereno & Maunsell, 1998), and their activity is predictive of the perceived motion direction of ambiguous motion stimuli, even to a greater extent than activity within the classical motion regions middle temporal and middle superior temporal (Williams, Elfar, Eskandar, Toth, & Assad, 2003). The behavioral experiments reported here were also directly prompted by our own electrophysiological work, where we recorded activity of single neurons within these posterior parietal regions. This line of research showed that rapid and automatic neural responses to novel, visually presented shapes, responses that previously had no known function, could be directly tied to the allocation of spatial attention and eye movements (H. M. Sigurdardottir & D. L. Sheinberg, unpublished observations).

There are, however, other possibilities. For example, motion processing might have a primary role, where shape directly affects the calculation of motion and overt and covert attention is then guided in the direction of movement. Also, if the shape and the target are grouped into one perceptual whole, then the effects reported here might not strictly be considered only spatial, and the enhancement for the target to which a shape points could be closely related to object-based attention (Driver & Baylis, 1989; Duncan, 1984; Egly, Driver, & Rafal, 1994). The mechanisms behind the behavioral results reported here need to be further studied.

It is worth noting that earlier attempts to find effects of shape directionality on orienting apparently failed (Zusne & Michels, 1964). Zusne and Michels (1964) did not find evidence for the idea that people would preferentially follow the main direction of a shape with their eyes. The discrepancy between this and the current study could be due to the fact that Zusne and Michels did not empirically define the shapes' directionality. Wolfe, Klempen, and Shulman (1999) also failed to find evidence for the hypothesis that varying an object's polarity, which roughly corresponds to our idea of directionality, led to efficient visual search. They concluded that there is little evidence for the preattentive processing of an object's polarity. We do not think that our results necessarily contradict those of Wolfe et al. As these authors themselves acknowledged, it is hard to interpret negative findings. More to the point, we are not claiming that directionality is an attribute that supports efficient visual search, or an almost instantaneous readout (e.g., pop-out) of some particular information. This kind of fast information detection might be fundamentally different from what we are talking about here, which is a stimulus-driven, rapid, and seemingly automatic shift in information sampling. An object's directionality also pushes attention away from the object itself. There is no specific reason why a strongly directional shape should itself be particularly rapidly detected in a visual search.

The affordance competition hypothesis (Cisek, 2007; Cisek & Kalaska, 2010) states that sensory information leads to the specification of current action possibilities that then compete with each other for ultimate selection for behavior (for uses of the word *affordance*, see also Gibson, 1986; McGrenere & Ho, 2000). Our results could be interpreted within this framework, as the shape of an object may lead to the specification of orienting affordances, or the possible ways to look and pay attention, some of which have a greater chance of being selected than others. Regardless, it is conceivable that the biases we report here can act as a front end to more traditionally defined affordance effects that involve physical interactions through reach and grasp (Bub & Masson, 2010; Cisek, 2007; Tucker & Ellis, 1998; for further discussion on the possible interplay between attention and affordance, see, e.g., Anderson, Yamagishi, & Karavia, 2002; Handy, Grafton, Shroff, Ketay, & Gazzaniga, 2003; Riggio et al., 2008; Vainio, Ellis, & Tucker, 2007). Under most circumstances, people look where they are about to act, so eye gaze precedes hand movements both inside the laboratory and in real-world tasks (Ballard et al., 1992; Hayhoe, 2000; Hayhoe & Ballard, 2005; Land & Hayhoe, 2001; Land, Mennie, & Rusted, 1999). Eye orientation also directly affects where people reach (Enright, 1995), and dorsal stream posterior parietal regions important for saccade and reach planning appear to share a common eye-centered coordinate frame (Cohen & Andersen, 2002). Visual attention also appears to be directed from one object to another when familiar, manipulable objects are positioned in a manner that facilitates their interaction, such as when a hammer and a nail are seen together in a position that would allow the hammer to strike the nail (Green & Hummel, 2006; Riddoch et al., 2011; Roberts & Humphreys, 2011; Yoon, Humphreys, & Riddoch, 2010). It would be very interesting to see what, if any, role the effects reported here play in such paired-object affordance effects.

Although eye and hand are clearly coupled, orienting biases such as those that we see here are in all likelihood not identical to reach and grasp affordances. It is not clear whether unfamiliar two-dimensional silhouettes on a computer screen afford reaching and grasping at all, and the effects are found even when the eyes and not the hands are used as effectors. It is also reasonable to assume that shape-induced orienting biases are evoked by objects beyond reach, such as birds in flight. In some cases, orienting biases might even directly oppose reach and grasp affordances. For example, when using a bottle or teapot, people tend to look at the bottle mouth or spout, or at the container into which they are pouring, instead of looking at their hands or the point of contact (Hayhoe, 2000; Land et al., 1999). Certain types of affordances and the effects reported here might nonetheless share the fundamental property of being "recognition free," involving a more-or-less direct coupling between vision and action.

Being able to circumvent recognition does not necessitate complete isolation from it. Within the field of computer vision, the detection of a shape's orientation is an often-used image preprocessing step applied before image registration and recognition (El-Sayed, Abdel-Kader, & Ramadan, 2010), and a number of algorithms have been developed to automatically detect the orientation and/or directionality of shapes (Cortadellas, Amat, & de la Torre, 2004; El-Sayed et al., 2010; Lin, 1996; Martinez-Ortiz & Žunić, 2010; Tzimiropoulos, Mitianoudis, & Stathaki, 2009; Žunić & Rosin, 2009; Žunić, Rosin, & Kopanja, 2006). The systematic and rapid extraction of an object's directionality could also serve a role in human object recognition (see, e.g., Leek & Johnston, 2006; Maki, 1986) by facilitating the search for and alignment to an existing object template or model.

In some cases, especially when objects are unfamiliar or if they are seen from an unfamiliar viewpoint, visual recognition is viewpoint dependent (Rock, 1973; Tarr & Bülthoff, 1998; Tarr & Pinker, 1989; Tarr, Williams, Hayward, & Gauthier, 1998). When a previously seen object is encountered again from another viewpoint, the new object instance (or, alternatively, an internal reference frame; Robertson, Palmer, & Gomez, 1987) is thought to go through an iterative transformation, such as a mental rotation (Carpenter & Just, 1978; Shepard & Metzler, 1971; Zacks, 2008; but see Farah & Hammond, 1988; Hayward, Zhou, Gauthier, & Harris, 2006; Turnbull & McCarthy, 1996) or alignment (Huttenlocher & Ullman, 1987), that orients the observed object with either a previously seen view or a privileged, canonical view (Jolicœur, 1985, 1990; Jolicœur & Landau, 1984; Palmer, Rosch, & Chase, 1981; Robertson et al., 1987; Tarr & Pinker, 1989). Stored object views have a particular orientation and handedness

(Tarr & Pinker, 1989) that can be thought of as having a specific directionality. The shortest path between a new and stored view could conceivably be calculated based on the angular difference between the directionality of the stored and observed object.

If a sufficient match to a stored representation is not found, directionality could be used to standardize the building of a new representation that is not completely dependent on the viewpoint from which an object happens to be first seen; the visual input could for instance be transformed and stored in a canonical directionality, such as upright. There indeed appears to be a favored view from which an object is most readily recognized (Palmer et al., 1981; see also Blanz, Tarr, & Bülthoff, 1999; Turnbull, Laws, & McCarthy, 1995), and damage to the parietal cortex can lead to specific deficits in recognizing objects from other, more unconventional views (Warrington & Taylor, 1973). The loss of the ability to automatically extract an object's directionality could hypothetically lead to such a deficit by preventing the correct normalization to a canonical object representation. The suggested route to recognition is just one of potentially many possible ways to identify an object (Jolicœur, 1990; Lawson, 1999; Vanrie, Béatse, Wagemans, Sunaert, & Van Hecke, 2002), some of which may not rely in any way on a shape's directionality. Independent of these speculations, here we have shown that shape influences processes beyond recognition, and these findings may provide insight into why object form may be processed in parallel throughout the visual brain.

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