Convexities move because they contain matter

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Figure–ground assignment to a contour is a fundamental stage in visual processing. The current paper introduces a novel, highly general dynamic cue to figure–ground assignment: "Convex Motion." Across six experiments, subjects showed a strong preference to assign figure and ground to a dynamically deforming contour such that the moving contour segment was convex rather than concave. Experiments 1 and 2 established the preference across two different kinds of deformational motion. Additional experiments determined that this preference was not due to fixation (Experiment 3) or attentional mechanisms (Experiment 4). Experiment 5 found a similar, but reduced bias for rigid—as opposed to deformational—motion, and Experiment 6 demonstrated that the phenomenon depends on the global motion of the effected contour. An explanation of this phenomenon is presented on the basis of typical natural deformational motion, which tends to involve convex contour projections that contain regions consisting of physical "matter," as opposed to concave contour indentations that contain empty space. These results highlight the fundamental relationship between figure and ground, perceived shape, and the inferred physical properties of an object.

Keywords: perceptual organization, motion—2D, shape and contour

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Introduction

Figure–ground assignment to a contour is a fundamental stage in visual processing. There are a number of related but distinct ways of characterizing the perceptual outcome of figure–ground assignment. These include the depth ordering of surfaces in the image (Rubin, 1921), the sign of curvature of sections of the contour (Barenholtz & Feldman, 2006), and the perceptual shape of the contour (Attneave, 1971; Baylis & Driver, 1995). Perhaps the most basic characterization of figure–ground assignment—although one that is not typically mentioned—is that it determines which image regions contain empty space and which regions contain physical matter. The rule is that the figural side of a shape—starting from immediately adjacent to the contour, up until the next encountered contour—will be perceived as containing physical matter (i.e., the "stuff" of which the objects in the image are made); the equivalent region on the ground side is perceived as containing empty space, through which the background is visible. With regard to convexity and concavity, this leads to the principle that convexities "contain" matter, whereas concavities "contain" empty space. Put more precisely (and as illustrated in Figure 1), in a 2-dimensional shape, a line segment connecting any two (and only two) points along a single, contiguous convexity (illustrated by the larger dashed lines in Figure 1) will exclusively cross *interior* regions of a shape—that is "matter"—whereas a line segment connecting two points of a contiguous concavity (shorter dashed lines in Figure 1) will exclusively cross exterior regions—that is "empty space."

The study of figure–ground assignment has a long history in experimental psychology, going back at least to Rubin and his famous Vase/Face stimulus (Rubin, 1921), and a substantial number of cues to figure and ground have been described. These include *size* (smaller areas assigned to figure; Koffka, 1935; Rubin, 1921), *symmetry* (Bahnsen, 1928; Kanisza & Gerbino, 1976; Machilsen, Pauwels, & Wagemans, 2009), *convexity* (Kanisza & Gerbino, 1976; Koffka, 1935; Stevens & Brookes, 1988), *lower region* (Vecera, Vogel, & Woodman, 2002), *familiarity* (Peterson, Harvey, & Weidenbacher, 1991), and *region/contour similarity* (Palmer & Brooks, 2008). In addition, a number of studies have reported dynamic cues to figure and ground based on properties of *moving* stimuli. These include several effects in which the common motion between a contour and neighboring texture elements leads to a figural assignment to the contour (Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kaplan, 1969; Palmer & Brooks, 2008; Yonas, Craton, & Thompson, 1987). More recently, a number of phenomena have been reported in which the motion of a bounding contour itself—independent of neighboring texture—influences figural assignment. In a recent study of dynamically translating contours, Barenholtz & Tarr (2009) found that subjects assigned figure so that the region the contour bounded was increasing, vs. decreasing, in area. Likewise, in a study investigating figural assignment to dynamically *deforming* contours (i.e., cases where one segment of a contour moves differently than other segments of the contour, leading to global non-rigidity), Barenholtz and Feldman (2006) found that subjects assigned figure so that the resulting contour deformation was consistent with specific

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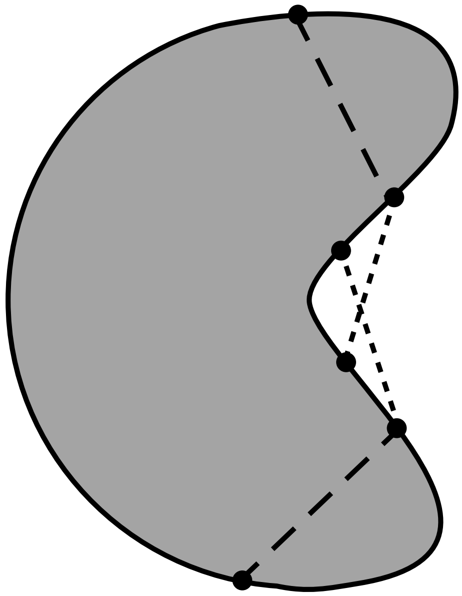

Figure 1. Convexities contain "matter" while concavities contain "empty space" (see text for details).

geometric properties of biological articulations. In particular, they found a preference to assign figure and ground such that an articulating vertex (i.e., where the vertex served as the fulcrum of rotation of an edge connected to another edge at the vertex) was concave. As described there, this "articulating concavity" preference is consistent with the properties of biological articulations.

Although articulation is perhaps the most familiar, there are a number of other categories of deformational motion common in the natural world including bending (e.g., a tree branch or a tentacle), expanding/contracting (e.g., a diaphragm during respiration), and stretching/compressing (e.g., a rubber band). One basic regularity that applies to all of these forms of deformational motion is that it is typically globally convex contours,[1] or "protrusions," that move *independently*—i.e., that segment of the shape moves in a coherent fashion while the rest of the shape is stationary or moves in a different direction. Globally concave "indentations," on the other hand, typically move either as part of the motion of the larger contour to which they belong or due to internal deformations; they do not typically move coherently, independently of the rest of the shape. For example, the contour of a finger—which is a globally convex protrusion—moves independently of the rest of the hand by articulating or by bending. However, the contour segment consisting of the sides of two adjacent fingers, along with the "webbing" between the fingers—which is a globally concave indentation—will typically only move either as part of the motion of the entire hand, or by deforming when the fingers move relative to one another. However, this region never moves coherently, independently of the rest of the hand. This regularity reflects the fundamental connections between the sign of contour curvature—as determined by figure–ground assignment—and the physical structure of an object: as discussed above, a strictly convex contour region, by definition, contains a region of the image consisting of the "matter" of which the object is made, whereas a strictly concave region contains empty space, as demonstrated in Figure 1. With regard to motion, the fact that the different sections of a convex contour are all connected to one another, via the matter lying between them, means that they form a physical unit that may move coherently, independent of the rest of the shape. A concavity, whose contour does not have this internal interconnectedness, does not form a coherent unit and is therefore unlikely to move independently of the rest of the contour to which it belongs. With regard to figure–ground assignment, this leads to the following prediction: given an independently moving contour, there should be a preference to assign figure such that the moving contour is convex (and thus bounds physical matter)—and not concave (and thus bounds empty space). The current paper presents a novel and highly general cue to figure–ground assignment: "convex motion," based on this regularity. The basic phenomenon is demonstrated in Figure 2 (animated demonstrations of all demos and experimental stimuli can be viewed at http://psy.fau.edu/~barenholtz/Convex_Motion_Demos.html). A contour that divides two colored regions introduces a figure–ground ambiguity; the central region in Figure 2A can be seen as a black

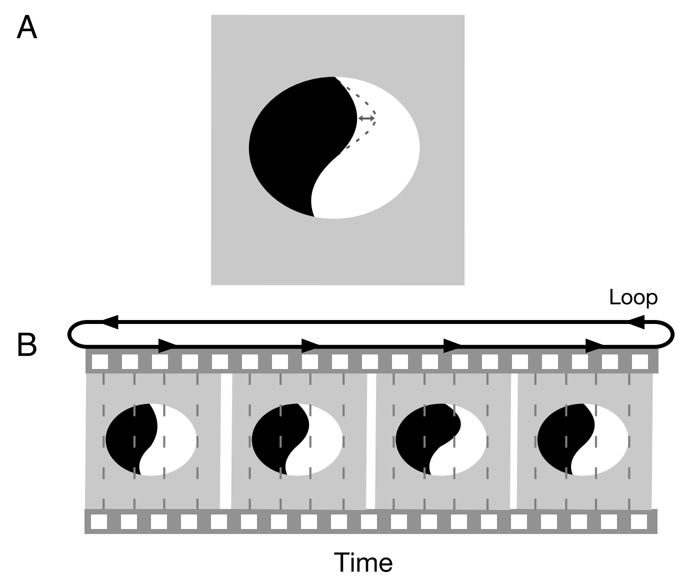

Figure 2. (A) A static stimulus with ambiguous figure–ground. It may be seen as either a black figure on a white background or vice versa. Motion is introduced by expanding and contracting one region of the contour (dashed lines). (B) A schematic diagram of a single motion cycle. Most people (~93%) report a figure–ground assignment in which the moving region is convex, black in this example.

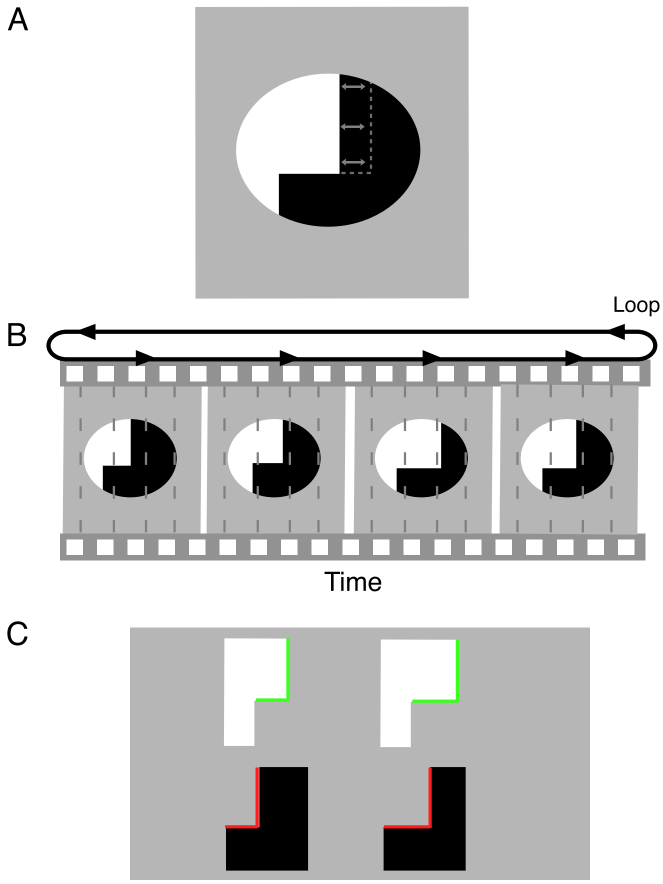

Figure 3. (A) Sample stimulus from Experiment 1. The static stimulus has ambiguous figure–ground. Motion is introduced (dashed lines) by translating one vertical edge back and forth (see text for details). (B) A schematic diagram of a single motion cycle, which was looped. (C) Depending on figure–ground assignment, either a black convex contour segment (shown with green edges, top) will be perceived in motion or a white concave region (shown with red edges, bottom). Subjects showed a preference for convex motion.

figure on a white background or a white figure on a black background. Figure–ground assignment here also determines the sign of curvature of the contour: if black is seen as figural, then the top section of the dividing contour has convex curvature and the bottom has concave curvature and the inverse is true if white is seen as figural. Additionally, with regard to the planar region adjacent to the contour, the figural assignment determines whether it contains matter or empty space: if black is figural, then the region bound by the moving contour (i.e., the black region enclosed by the top curve in this example) contains black "matter" whereas in a white-as-figure interpretation, the same region will contain empty space through which a black background is visible.

While the static stimulus in Figure 2A is inherently ambiguous, with the introduction of an expanding/contracting motion of one region of the contour (schematically illustrated in Figure 2B), the stimulus is typically "disambiguated": observers almost always report a figural assignment in which the moving contour section is convex (approximately 93% of the time in pilot experiments), which would correspond to black in the current example. This preference for convex vs. concave contour motion presumably reflects the fact that this figural assignment results in more physically plausible motion, based on the considerations described above; that is, there is a preference for motion that involves a convex contour bounding matter as opposed to a concave contour bounding empty space.

The current paper presents six experiments examining this convex motion bias using a figure–ground discrimination task. The basic methodology was similar across all of the experiments: subjects viewed a polygonal contour that formed the boundary between two uniformly colored regions, viewed through a virtual "aperture" (polygonal contours offer a significant advantage over smooth shapes like the one in Figure 2 in terms of isolating critical shape properties). On each trial, some portion of the contour moved and subjects were asked to report which color appeared to be moving "in front" of the other. Since assignment of figure and ground also determined the sign of curvature (convex or concave) of a given region, a preference for convex motion might be present in the form of a bias to assign figure such that the moving region is seen as convex rather than concave.

Experiment 1

Experiment 1 used stimuli consisting of animation sequences containing a simple figure–ground display consisting of a "step"-shaped contour, separating two colored regions (Figure 3A). This leads to an ambiguous display; in this case, the stimulus may be interpreted as a black surface on a white background or a white surface on a black background. On each trial, a single edge of the contour was translated back and forth in an oscillatory pattern, while the other region of the contour was stationary, leading to a deformational motion of the contour (Figure 3B). Based on the assignment of figure and ground, this motion carries at least two possible likely interpretations, demonstrated in Figure 3C. In the black-as-figure interpretation (Figure 3C, top), a globally convex[2] region of the shape—bounding matter—is in motion whereas in the white-as-figure interpretation (Figure 3C, bottom), a globally concave region—bounding empty space—is in motion. A preference for convex motion in this case would thus lead to a percept in which black is figural.

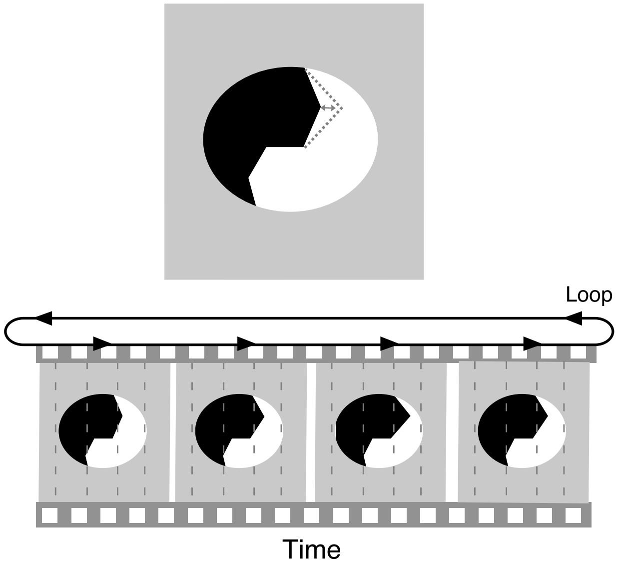

Figure 4. (Top) Sample stimuli from Experiment 2. The motion in this experiment involved the horizontal motion of one of the pointed vertices back and forth (dashed lines). (Bottom) A schematic diagram of a single motion cycle. In this example, a convex motion interpretation would lead to black being seen as figural. Note that this does not constitute "part motion" as determined by parsing at concavities.

Methods

Subjects

Fifteen Florida Atlantic University students naive to the purpose of the experiment participated in the study for course credit.

Stimuli

Stimuli were computer-generated, animation sequences consisting of two, differently colored regions (the color of each region was randomly chosen on each trial[3]), separated by a boundary made up of three approximately equally sized edges arranged in a "step" configuration. These regions were presented through a circular virtual "aperture" on an otherwise gray screen (i.e., during the motion sequence, sections of the moving contour became "occluded" and "revealed" as they moved in and out of the aperture). The circular aperture measured approximately 2.3° visual angle in diameter. Each of the vertical edges (based on the orientation of the stimulus in Figure 3; the actual stimuli were randomly rotated across trials) extended to half of the total diameter of the aperture and was separated by the horizontal edge, whose length ranged with between approximately 1/3 and 2/3 of the vertical edge throughout the motion sequence. The starting midpoint (i.e., before motion was introduced) of the horizontal edge was the horizontal and vertical midpoints of the screen. During each trial, one of the vertical edges of the boundary was translated forward and backward in an oscillatory pattern, horizontally (again, relative to the canonical orientation in the figure; see Figure 4B). The motion consisted of translating the vertical edge approximately 0.4° in one direction and then back in the opposite direction, which was then repeated to generate an oscillating motion pattern. Each full oscillation took approximately 0.3 s and the entire motion sequence consisted of between 5 and 7 oscillations, for a total animation time of approximately 1.5 to 2.1 s. Because a recent study by Barenholtz and Tarr (2009) found that there is a preference in figure–ground displays for motion in which the region bound by the contour is getting larger rather than smaller ("advancing" rather than "receding"), the initial position (or phase) of the moving edge was randomly selected from the oscillatory sequence, ensuring that the first observed motion was equally likely to be an advancing or receding motion. The orientation of the entire stimulus was randomized on each trial.

Procedure

Subjects were instructed that they would be viewing colored regions in motion and that their task was to report, after a brief delay, which color had been "moving in front" during the motion display. On each trial, the subject viewed a fixation cross for 500 ms, followed by the motion sequence described above (~1.5–2.1 s), followed by a gray screen for 1 s. Afterward, a test screen appeared in which two square color patches, corresponding to the two colors present in the stimulus sequence, were presented to the right and left (randomly assigned) of the screen. The subject was instructed to choose which color was the one that they had perceived as "moving in front" during the motion sequence. A "convex" response was recorded if the reported figural assignment led to a shape configuration in which the moving region was protruding from the assigned figure. Each subject performed 85 trials.

Results

The percentage of trials on which the choice of figure–ground assignment corresponded to the moving region being convex was calculated. Across all subjects, the percentage of trials on which a convex motion was reported was 78% (SE = 5%). This preference was significantly greater than chance, $t(14) = 4.693$, $p < 0.0001$.

Discussion

The results of Experiment 1 demonstrate that there is a strong preference for convex vs. concave motion and that this preference can serve to disambiguate otherwise ambiguous figure–ground displays. This preference likely reflects regularity in natural motion in which convex regions are more likely to move independently than concave regions. Previous reports have found a preference for motion that is consistent with the regularities of typical biological motion, specifically articulations of limbs at joints (Barenholtz & Feldman, 2006). The results of Experiment 1 represent a much more general principle, one that applies to other forms of deformational motion as well. However, although the stimuli used in Experiment 1 did not contain any articulatory motion per se (in the form of a rotating joint), choosing a convex motion interpretation for these stimuli did carry an additional "biological" feature shared with articulations. Namely, it led to motion that involved a *part,* based on partitioning at regions of negative curvature (Hoffman & Richards, 1984). As can be seen in Figure 3C, the black-as-figure interpretation leads to a percept in which the two moving edges bound a single part—as defined by segmenting at the concave (in this figure–ground assignment) vertex—whereas the white-as-figure interpretation leads to a motion in which the two moving edges bound two different "parts." Thus, the preference found in Experiment 1 could conceivably be due to a preference for "part motion" of the sort that occurs during articulation, as in Barenholtz and Feldman (2006). However, as discussed earlier, the principle of convex motion applies much more generally and is not restricted to articulatory motion. To determine whether there is a similar bias for convex motion even when part motion is not involved, Experiment 2 employed a stimulus in which assigning convexity to the moving region did not lead to motion of a part as determined by parsing at concavities.

Experiment 2

Experiment 2 was identical to Experiment 1 with the exception that the boundary separating the two colored regions contained an additional vertex along each vertical edge, forming a point (Figure 4).

The motion in Experiment 2 consisted of one of these points translating inward and outward in an oscillatory pattern (Figure 4B), producing a polygonal version of the expanding/contracting motion in the pilot stimuli shown in Figure 2. As in Experiment 1, a preference for convex motion should lead to a preference to assign figure and ground to one region (in this case, black). However, unlike Experiment 1, this convex assignment does not lead to a "part motion," since a convex figural assignment results in a moving region that is connected to the rest of the contour at a convexity, not a concavity.

Methods

Subjects

Ten Florida Atlantic University students who had not participated in Experiment 1 and who were naive to the purpose of the experiment participated for course credit.

Stimuli and procedure

Stimuli and procedure were identical to those used in Experiment 1 except for the fact that the motion involved the additional points described above and illustrated in Figure 4. The additional points were positioned approximately 0.4° visual angle away from the midpoint of the vertical edge in Experiment 1 and the motion consisted of a horizontal translation of one of these points 0.3° in alternating directions for between 5 and 7 oscillations.

Results and discussion

Across all subjects, there was a preference to report figure–ground assignment that was consistent with a convex region in motion on 75% of trials (SE = 5%). This preference was significant, $t(14) = 4.163$, $p < 0.001$. Unlike Experiment 1, assigning figure consistent with convex motion did not lead to an articulation-like "part motion." If compared to a "natural" motion, the stimuli in Experiment 2 most closely resembled an expansion and contraction, such as occurs during respiration.

Experiment 3

While the stimuli used in Experiments 1 and 2 were globally symmetrical with regard to convexity (i.e., assigning figure–ground to either side of the contour led to equally convex global shapes), they were not, of course, symmetrical in the local region of the motion. Some recent evidence suggests that figure–ground assignment can be strongly influenced by the local contour geometry in the region to which one is attending. Kim and Feldman (2009) found that subjects making judgments about a small section of dynamically perturbing contour often made "globally inconsistent" figure–ground assignments, with the same contour feature (an indentation in an otherwise circular shape) being treated as convex in one location and concave in another. Thus, one possible concern with regard to Experiments 1 and 2 is that subjects are making a figure–ground assignment based on the local geometry of the moving contour section alone. In this case, the preference observed in Experiments 1 and 2 may not be due to a preference for convex *motion* per se, but rather due to a "standard" convexity bias—that is, one

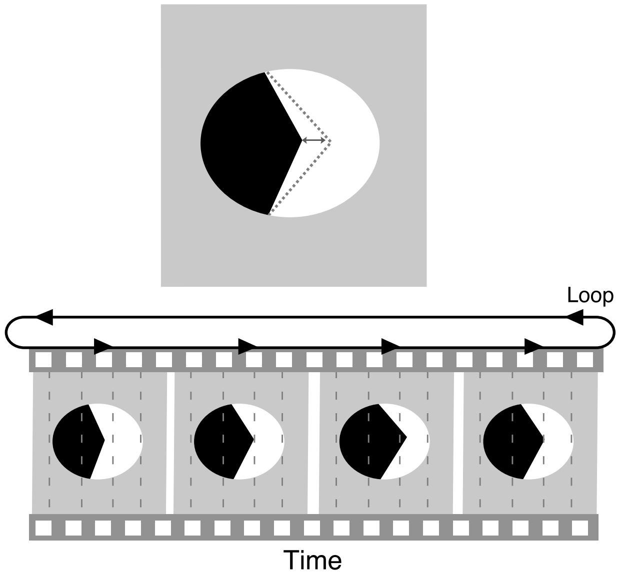

Figure 5. (Top) Sample stimuli from Experiment 4 consisting of a single triangular contour. Motion is introduced by translating the central vertex horizontally back and forth (dashed lines). (Bottom) A schematic diagram of a single motion cycle. In this example, a convex motion interpretation would lead to black being seen as figural.

that is present even without motion—applied to the local region of the contour that is moving. The most basic version of this account would be that subjects are simply saccading to the region of the motion and performing figure–ground assignment based on the contour that is most "local" to the point of fixation. To address this possibility, Experiment 3 used stimuli identical to Experiment 1 using a task in which subjects had to maintain fixation on a location away from the stimulus throughout the trial. This ensured that there was no relationship between where subjects were fixating and any figure–ground preference they demonstrated. In addition, the distance of the stimulus from fixation ensured that the motion component of the stimulus fell well in the periphery, allowing us to determine whether the bias persists in peripheral vision.

Methods

Subjects

Fifteen Florida Atlantic University students who had not participated in any of the other experiments and were naive to the purpose of the experiment participated for course credit.

Stimuli and procedure

Stimuli and procedure were identical to those used in Experiment 1, except that on each trial a fixation cross was present throughout the duration of the motion sequence. The fixation cross was randomly displayed on either the right or left side of the screen, with its center approximately 6.5° away from the center of the screen. The motion stimulus was identical to that used in Experiment 1 and was presented centrally as in earlier experiments. Subjects were instructed to hold fixation on the cross while the motion was taking place until the response screen was shown. Each subject performed five practice trials under supervision of the experimenter to ensure that they understood and followed the instructions, i.e., maintain fixation away from the motion. (Although no eye tracking was performed to ensure compliance, subjects reported no difficulty in maintaining fixation on the cross in post-experiment interviews.)

Results and discussion

Across all subjects, there was a preference to report figure–ground assignment that was consistent with a convex region in motion on 75% of trials (SE = 4%). This preference was significant, $t(14) = 5.87$, $p < 0.0001$. A clear convexity bias is present even when subjects are not fixating in the region of motion, eliminating location of fixation as a possible explanation for the phenomenon. Furthermore, Experiment 3 demonstrates that the convex motion bias persists in the periphery.

Experiment 4

Although the results of Experiment 3 suggest that the preference does not arise because of the location of fixation, it is still possible that motion is somehow causing subjects to make a local figure–ground assignment in the neighborhood of the motion. For example, subjects may still be *attending* to that area of the stimulus, even though they are not fixating there. Again, the preference in this case would not be for convex motion per se but would consist of a standard convexity bias applied to a local region that is in the neighborhood of attentional fixation. A related, but subtly different, possibility is that the motion of one region of the contour may perceptually "isolate" that segment from the rest of the contour, effectively forming a disconnected perceptual object. The bias observed might then depend on a standard convexity bias applied to the asymmetrical, isolated contour region. To address this possibility, Experiment 4 employed a stimulus containing just a single v-shaped vertex and compared figure–ground assignment when the vertex was static vs. when the point was translated, leading to a deformational motion similar to that used in Experiment 2 (Figure 5). Note that, even though the entire dividing contour was moving in these displays, the nature of the motion was

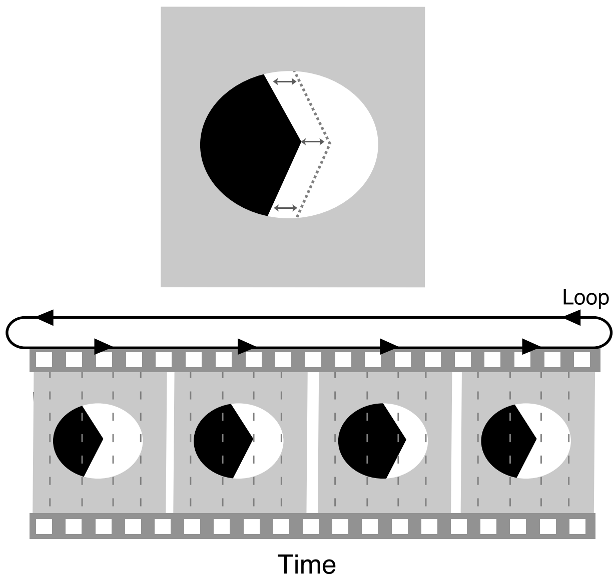

Figure 6. (Top) Sample stimuli from Experiment 5. Motion is introduced by translating the whole v-shaped contour horizontally back and forth, leading to a rigid motion. (Bottom) A schematic diagram of a single motion cycle.

identical to that of the portion of the contour that was moving in Experiments 2 and 3.

The underlying logic of this experiment was given as follows: if the role of motion in earlier experiments was simply to draw attention to, or isolate, the moving contour, then there should be no observed difference between the static and motion conditions in this experiment, since the motion cannot serve to further isolate the contour. If, on the other hand, motion itself is critical in producing the observed biases, then there might be an additional preference in the motion condition beyond any observed in the static condition. Of course, unlike the previous experiments, the stimulus type used in Experiment 4 *does* carry a figure–ground cue of convexity, even when the stimulus is static, which predicts the same response as the moving convexity cue. However, pilot experiments performed prior to Experiment 4 suggested that the convexity bias is actually relatively weak for this particular class of stimuli when shown statically. This is most likely due to the presence of other, randomly assigned, potential figure–ground cues—such as color, luminance, and orientation—which probably generate some preferences in their own right independent of convexity/concavity but are overridden by a strong cue such as the motion in Experiments 1–3. Thus, the critical question in this case is not whether there will be a bias for convex but whether there will be a significant difference in the magnitude of a convexity bias between the static and motion conditions. Any increase in a convexity bias in the motion condition can be attributed to the motion itself, not to an isolation of the contour due to attention or some other mechanism.

Methods

Subjects

Twenty Florida Atlantic University students who had not participated in any of the other experiments and naive to the purpose of the experiment participated for course credit.

Stimuli and procedure

The stimulus consisted of two colored regions separated by a v-shaped boundary, viewed through a virtual aperture as in Experiments 1 through 3 (Figure 5). The central vertex of the v-shaped contour consisted of a 125-degree angle (starting position; the angle changed during motion) positioned vertically at the center of the screen, with a horizontal position approximately 0.3° visual angle away from center, in order to equate the areas of the two colored regions. Each subject performed two blocks of trials: a static condition, followed by a motion condition. The observer's task was identical in each one: to report which color they had seen "in front" of the other. In the motion condition, the central vertex of the v-configuration was translated approximately 0.4° visual angle in alternating directions while the position of the opposite ends of the two edges (where they met the edge of the aperture) remained stable. This led to a deformational, "pulsating" motion of the contour (Figure 5, bottom) identical to the motion of the moving portion of the contour in Experiment 2. The number of cycles and starting/end point of the motion sequence were the same as in Experiments 1–3. In the static condition, on each trial, the stimulus consisted of a single frame of the animation sequence, chosen randomly and displayed for 1.7 s: the approximate average presentation time in the motion condition.

Results and discussion

Subjects showed a preference for a convex figure in both the static condition (mean = 59%, SE = 5%) and the motion condition (mean = 80%, SE = 3%). However, this preference only reached significance in the motion condition, $t(19) = 10.106$, $p < 0.0001$, whereas it only reached marginal significance in the static condition, $t(19) = 1.882$, $p = 0.07$. A separate t-test comparing the preferences in the static and motion conditions found that the difference between these conditions was highly significant, $t(19) = 4.351)$, $p < 0.0001$. This demonstrates that even when the critical contour is completely isolated, there is an effect of motion on the preference to assign figure and ground such that the motion involves a convexity.

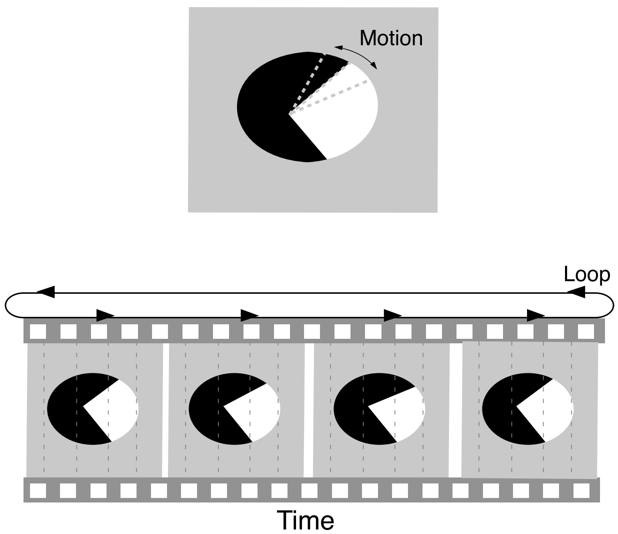

Figure 7. Example of stimuli (top) and motion sequence (bottom) from Experiment 4 of Barenholtz and Feldman (2006) demonstrating the "articulating concavity" bias. Subjects showed a strong bias to assign figure–ground so that the central vertex was concave (i.e., black-as-figure interpretation in this example), consistent with an articulating, hinged, joint.

These results suggest that the results of Experiments 1–3 were not due to the motion somehow leading to the application of a standard convexity cue to the moving region; even with the critical contour completely isolated, motion dramatically increased the probability of a convex assignment.

Experiment 5

All of the preceding experiments involve deformational motion of the contour. Would a convexity bias be present for a rigidly moving contour as well? Experiment 5 tested this using a stimulus similar to Experiment 4, with the difference that the v-shaped contour translated rigidly rather than deforming (Figure 6). On the one hand, as discussed above, both convexities *and* concavities frequently move rigidly as part of the motion of the larger shape to which they belong. It is independent motion—which must be deformational as in Experiments 1–3[4]—that is specifically associated with convexities. Thus, there may be no convexity bias in the case of rigid motion, since such motion may be interpreted as reflecting a rigid translation of a larger shape to which the visible contour belongs. However, it is also possible that since an independently moving contour is typically convex, the bias will generalize to any moving contour that is viewed in isolation.

Methods

Subjects

Fifteen Florida Atlantic University students who had not participated in any of the other experiments and were naive to the purpose of the experiment participated for course credit.

Stimuli and procedure

Stimuli and procedure were identical to Experiment 4, except that the motion sequence consisted of a rigid translation of the v-shaped contour (Figure 6). The motion sequence consisted of a translation of the contour in the direction of the bisector of the central angle approximately one half a degree visual angle in both directions. The number of cycles and starting/end point of the motion sequence were the same as in Experiments 1–4. As in Experiment 4, there is a convexity cue present in these stimuli even without motion. Therefore, each subject performed a static and motion block to see whether there was a *difference* in preference due to the motion. Each block consisted of 40 trials for a total of 80 trials per subject.

Results and discussion

In the static condition, subjects showed no significant preference for convexities (mean = 52%, $SE = 2\%$, $p > 0.6$ by t-test). In the motion condition, subjects showed a preference for convexity (mean = 0.63, $SE = 0.05$). This preference was significant, $t(14) = 2.926$, $p = 0.01$. Thus, as in Experiment 4, motion of the contour led to a higher proportion of convex responses. However, this preference appears to be considerably less pronounced than the convexity bias reported in Experiment 4, in which respondents chose convex on 80% of trials. To test this, an additional t-test was performed comparing the responses in the motion conditions of Experiment 4 with those of Experiment 5, finding that the difference between the two cases was significant, $t(33) = 3.258$, $p < 0.01$. This suggests that the moving convexity bias generalizes to rigid motion, but only weakly. The full convex motion bias is only present when the observed motion is consistent with independent movement of the contour.

Experiment 6

The results of Experiments 4 and 5 bear interesting relations to those of the final study in Barenholtz and Feldman (2006). Figure 7 illustrates the "articulating concavity" bias as demonstrated in Experiment 4 of

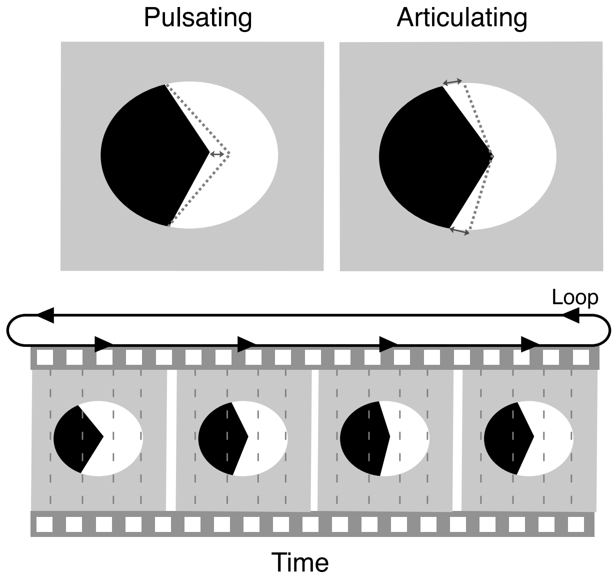

Figure 8. (Top) The two types of motion used in Experiment 6 (see text for details). (Bottom) A schematic diagram of a single motion cycle in the Articulating motion condition. In this example, a concave interpretation (as favored by subjects) would yield a white-as-figure assignment.

Barenholtz and Feldman (2006). There, subjects showed a preference to perceive a contour in which one edge rotated at a central vertex as *concave*, which may be contrasted with the convex motion preference described here. However, while the stimuli in these studies are superficially similar, there are two major differences between that stimulus and the one described here: First, in that experiment, only one edge was in motion, and therefore, it did not "contain" any region of the image; as proposed above, the convexity bias observed here is likely due to a preference for moving contours to be perceived as containing matter. Second, because the central vertex articulates without changing its position in Barenholtz and Feldman (2006), the perceived motion consists only of a deformation of a concavity or convexity, *not* a global translational motion of the contour. That is, the global position[5] of the contour in this case remains fixed. This is in contrast with Experiments 4 and 5 of the present study, where, because of the translational motion of the vertex, the entire contour is perceived to be moving globally through space.

Thus, there are at least two properties—"containing motion" and "translational motion"—that are present in the current study that may be responsible for the convexity bias obtained in the present study as compared with the concavity bias in Barenholtz and Feldman (2006). From a theoretical standpoint, it is likely, based on the considerations discussed earlier, that containing motion without translational motion will not yield a convexity bias; deformations of a concavity involving the surrounding edges occur frequently, such as when the concave region between two fingers deforms when both fingers move. To test whether translational motion is indeed necessary to produce the convexity bias or whether containing motion is sufficient, Experiment 6 used a stimulus similar to that used in Experiment 4 but with two different motion conditions (Figure 8, top): in the "Pulsating" condition, the stimuli were identical to those used in Experiment 4, consisting of a translation of the central vertex. In the "Articulating" condition, the stimulus was similar to the stimuli used in Barenholtz and Feldman (2006), with hinged motion at the central vertex, with the exception that *both* edges underwent the rotational motion. Note that both of these conditions consist of "containing motion," as discussed above; indeed, the deformational motion of the contour is very similar in the two cases, consisting of a "pac-man"-like narrowing and widening of the central angle. However, since the central vertex remains static in the Articulating condition, the contour does not undergo global motion and instead appears to be deforming in place. If, as predicted, global motion is necessary to produce the convexity bias, we can expect a reversal in preferences in the two conditions with a convexity bias in the Pulsating condition and a concavity bias in the Articulating condition. If, however, containing motion alone is sufficient to produce the bias, then there is likely to be a convexity bias in both conditions. In order to most directly compare the two motion conditions, Experiment 6 employed a mixed block design in which each subject was presented with both kinds of motion shown in random sequence in order to determine whether the different motion types could induce a reversal of preferences across individual trials.

Methods

Subjects

Ten Florida Atlantic University students who had not participated in any of the other experiments and were naive to the purpose of the experiment participated for course credit.

Stimuli and procedure

The stimulus consisted of a v-shaped contour similar to the stimulus used in Experiment 4. There were two types of motion sequences: Pulsating and Articulating. The Pulsating sequence was identical to the motion sequence in Experiment 4. In the Articulating sequence, the two edges of the contour rotated around the central vertex—which remained stationary—in opposite directions, generating a "pac-man"-like motion pattern, in which the angle of the vertex grew narrower and wider (Figure 8, bottom). The stimuli in the Articulating condition were designed so that the change in angle, which resulted from the rotation of the edges, matched the change in angle in the Pulsating condition, which resulted from the translation of the central vertex. This corresponded to a change in angle of 15 degrees in each direction (with a starting position of 125 degrees). The number of cycles and choice of the starting/end point of the motion sequence were the same as in Experiments 1–5. Each subject performed a single mixed block consisting of 40 trials of both types of motion presented in random order.

Results and discussion

Because the two types of motion lead to opposite predictions in terms of convexity/concavity bias, they were analyzed independently. In the Pulsating motion trials, there was a strong tendency to report a convex figure (mean = 79%, *SE* = 5%) $t(9) = 5.086$, $p < 0.0001$. Thus, this condition replicated the results of Experiment 4. However, in the Articulating trials this preference was reversed, with a strong tendency to report a concave figure (mean = 75%, *SE* = 4%, $t(9) = 6.099$, $p < 0.0001$). That is, subjects switched their preference from convex to concave across trials, based on the type of motion in the display. In particular, in the Articulating motion cases, where there was no global motion of the contour—even though there was containing motion—there appears to have been no convexity bias, with the "articulating concavity" bias (Barenholtz & Feldman, 2006) leading to a concave-as-figure interpretation. Thus, as predicted, global motion of the contour is necessary to produce the convex motion bias.

General discussion

The current findings support the presence of a highly robust figure–ground assignment cue that is based on a preference to perceive independently moving contour sections as convex. This result expands the list of recently reported figure–ground cues based exclusively on the motion of the bounding contour. Like the "articulating concavity" bias (Barenholtz & Feldman, 2006) and the "advancing region" bias (Barenholtz & Tarr, 2009), convex motion is based on the dynamic properties of the contour region itself, not the neighboring texture as in earlier experiments (Gibson et al., 1969; Kaplan, 1969; Palmer & Brooks, 2008; Yonas et al., 1987). In addition, like the articulating concavity bias, the principle described here is consistent with properties of typical biological motion. However, convex motion is much more general and is not confined to cases, such as joint movement, in which there is articulatory motion. Indeed, it is likely that the preference does not depend on any "biological" interpretation at all. Unlike the smooth-shaped stimuli described in the original pilot study (Figure 2), the stimuli used in the actual experiments are highly simplified and do not look particularly "biological" (and in fact the preference in these experiments never reached the same level of reliability as for smoothed shapes described in the pilot experiment). Nevertheless, these stimuli produced a strong convex motion bias suggesting that this bias might reflect a somewhat "lower level" mechanism in which independently moving contours are interpreted as being convex, independent of an interpretation that is based on biological motion. However, it is likely that the *utility* of such a bias is to interpret biological deformational motion, in which convex protrusions are more likely to move independently.

As discussed above, assigning figure and ground carries implication both with regard to the sign of curvature of the contour as well as whether the regions bounded by the contour contain matter or empty space. An important question with regard to the current results is which of these perceptual outcomes is driving the preference. Thus, it could be that the preference depends specifically on assigning a positive sign of curvature to a moving contour. Alternatively, the preference could depend on assigning figure so that the image region contained by the moving contour contains matter rather than empty space. Although this ambiguity applies to other figure–ground cues as well, it is particularly relevant to the current cue since—as discussed—the coherent motion of a contour may signal the interconnectedness of the different portions of the moving contour. However, because both of these are direct outcomes of figure–ground assignment, they are difficult to disambiguate, and the current results do not favor either interpretation. Regardless of the underlying mechanism, however, the current results highlight an aspect of figure–ground assignment that is not typically addressed in discussions of figural assignment: determining whether the regions defined by the contour contain matter or empty space. Thus, the current results underscore the fundamental relationship between perceived shape and the inferred physical structure of objects.

The convex motion preference described here bears interesting parallels to the results of a recent study by Bertamini and Hulleman (2006) who found that it is nearly impossible to perceive the motion of a contour with purely concave curvature, i.e., a *hole*. They found that subjects viewing moving holes, presented using binocular disparity, often spontaneously reversed depth order so that the holes were seen as bumps. This may be compared with the current results, in which it was less likely, although certainly not impossible, to perceive concave motion; on a substantial minority of trials, subjects in the current experiments did report a figural assignment consistent with concave motion. Indeed, using the same smooth-shaped stimuli described in the pilot experiment described in Figure 2, but with a texture providing a strong ground cue on the side of the contour consistent with convex motion (due to accretion and deletion of texture elements), we found that subjects can and do report seeing the independent motion of a concave contour (an example of this stimulus may also be seen at http://psy.fau.edu/~barenholtz/Convex_Motion_Demos.html). A critical difference between concavities and holes is that the motion of concavities, while not typical, is physically plausible. For example, nudging the webbing between two fingers with another finger produces concave deformational motion. However, there is no equivalent, physically plausible, situation under which holes will translate rigidly, as in Bertamini and Hulleman's (2006) stimuli. The visual system therefore seems to reject a moving hole interpretation as an impossibility.

The current findings add to a fairly extensive literature concerning the difference in the psychological representation of concavities and convexities. Several studies have reported an advantage for the detection of concavities or their properties using paradigms of change detection (Barenholtz & Feldman, 2003; Bertamini & Farrant, 2005; Cohen, Barenholtz, Singh, & Feldman, 2005; Vandekerckhove, Panis, & Wagemans, 2007) as well as visual search (Hulleman, te Winkel, & Boselie, 2000). Recent studies have provided a more complex picture however, in which the role of global shape structure (Bertamini & Farrant, 2005) as well as local shape context (Bertamini, 2008) play an important role in producing some of these advantages. On the flip side, an advantage for *convexities* has also been reported in a number of tasks including positional judgment (Bertamini, 2001; Gibson, 1994) and symmetry detection (Hulleman & Olivers, 2007). The current study suggests that, with regard to motion, convexities and concavities are not treated equally by the visual system: given a choice between the two, the visual system prefers to see moving convexities compared with concavities. However, these results do not indicate whether there would be an advantage in perceiving the motion of convexities vs. concavities under conditions where the figural assignment has already been determined. As mentioned above, it is possible to see concave motion under the right conditions, such as with appropriate texture cues. Further experiments will be needed to assess the role of sign of curvature on motion detection under these conditions.

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Footnotes

[1]The terms "global" convexity and concavity are used here as in Barenholtz and Tarr (2008) and refer to whether some section of contour as a whole protrudes into or out of a shape. Strictly speaking, true concavity and convexity refer only to local curvature, as defined by differential geometry. Thus, a "globally convex" protrusion, such as an arm, may contain sections of both concave and convex curvatures. The global convexity or concavity of a contour region may be defined precisely by considering the contribution of the specific contour region to the convex hull of the entire shape; the addition of a global concavity will not change the shape of the convex hull while the addition of a global convexity will change the shape of the convex hull.

[2]While the moving vertex does have local curvature whose sign will be determined by figure–ground assignment, the rest of the contour has straight edges that have no curvature. However, the entirety of the moving contour is described here as globally convex or concave as detailed in Footnote 1.

[3]The colors of the two different regions were each chosen by randomly selecting two points in RGB color space (with values chosen from between 200 and 255 for each component of the triple) that were at least 50 points in Euclidian distance from one another in the color space.

[4]In Experiment 4, the moving contour was isolated and so cannot be said to have moved independently—however, the type of deformational motion used in Experiment 4 was an isolated version of the motion used in Experiment 2 and is thus consistent with independent motion.

[5]The concept of global position can be made more precise by reference to the main axis of the shape defined by the contour, which (regardless of figural assignment) remains completely fixed in the articulating case but which grows shorter and longer in the Pulsating case. Thus, in the Articulating condition that shape may be described as deforming "in place" while in the Pulsating condition it is "in motion."

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