Infants and adults use line junction information to perceive 3D shape

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Two experiments investigated infants’ and adults’ perception of 3D shape from line junction information. Participants in both experiments viewed a concave wire half-cube frame. In Experiment 1, adults reported that the concave wire frame appeared to be convex when it was viewed monocularly (with one eye covered) and that it appeared to be concave when it was viewed binocularly. In Experiment 2, 5- and 7-month-old infants were shown the concave wire frame under monocular and binocular viewing conditions, and their reaching behavior was recorded. The infants in both age groups reached preferentially toward the center of the wire frame in the monocular condition and toward its edges in the binocular condition. Because infants typically reach to what they perceive to be closest to them, these reaching preferences provide evidence that they perceived the wire frame as convex when they viewed it monocularly and as concave when they viewed it binocularly. These findings suggest that, by 5 months of age, infants, like adults, use line junction information to perceive depth and object shape.

Keywords: line junctions, depth perception, infant perception, object perception, spatial layout


Introduction

The goal of this research was to examine whether adults and infants have a vivid experience of 3D layout when presented with a pattern of line junctions. The visual information projected onto the retina of each eye is twodimensional (2D). However, the adult visual system recovers the three-dimensional (3D) layout of surfaces, objects, and events (Gibson, 1950). This transformation is impressive considering that the image on the retina could be generated by an infinite number of possible 3D layouts (Biederman, 1987). It is likely that the human visual system employs constraints that minimize the possible interpretations of the ambiguous retinal image.

For the purposes of this paper, “constraint” refers to an a priori assumption, which reflects properties of the natural environment, made by the visual system in order to interpret an ambiguous 2D image on the retina. The visual system’s use of constraints has been demonstrated in human adults in several domains (see Pizlo, 2001 for a review).

One constraint that is employed by the visual system is a limitation of the possible interpretations of line junctions. Line junctions provide information regarding the 3D shape of objects. They can be compelling enough to create a convincing impression of 3D shape, even when drawn on a 2D surface, as is seen in line drawings.

The lines in a drawing of an object are interpreted as occluding boundaries, corners between two surfaces (dihedrals) that are either concave or convex, and multihedral angles in which more than two surfaces meet to create a corner. Waltz (1972) used the relationship between lines and their junctions to create one of the first effective computer vision programs that could detect impossible objects and recover object shape from line drawings (see Winston, 1992 for an account of Waltz’s work). Using a labeling scheme created by Clowes (1971) and Huffman (1971) to identify lines as outer edges and convex or concave dihedrals, Waltz demonstrated that there were a limited number of possible 3D layouts of line junctions, given three assumptions: (1) Small changes in viewpoint do not change the classification of line junction (e.g., a convex corner), (2) objects have thickness and are

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not made of sheets, (3) objects are opaque. Of particular interest for this paper is Waltz’s description of possible interpretations of the lines that make up a drawing of an object, such as the cube presented in Figure 1. Waltz demonstrated that, using constraints provided by the possible interpretations of line junctions, a Y-shaped junction in the center of a cube-like form could only be generated by a convex, rather than a concave, trihedral.

Although line junctions can evoke an impression of three-dimensionality in a line drawing, it is not clear that line junction cues create the same experience of depth elicited by cues such as motion parallax and binocular disparity. In this paper, we explored whether line drawings are experienced when cues for the flatness of a display (e.g., the texture of the flat piece of paper on which it is drawn and binocular information) are absent. Participants in the present experiments viewed a concave wire frame that contained an internal, Y-shaped vertex (Figure 2).

### Experiment 1

In **Experiment 1**, adults viewed the concave wire frame under monocular and binocular conditions. We hypothesized that adults would perceive the frame as convex under monocular viewing conditions. If line junction information is sufficiently powerful, the frame’s line junctions must be interpreted as specifying convexity in the monocular condition, when binocular information for depth is absent. To produce this effect, conflicting cues for depth given by linear perspective and motion parallax must be overcome. When the viewer moves, the physically more distant central vertex moves at a slower velocity than the closer corners of the frame. Normally, this motion parallax would specify concavity, due to the faster motion of some vertices relative to others. However, during monocular viewing, when the center vertex is perceived as nearer than the outer corners, the perception of the frame as convex is in conflict with motion parallax. The only way this could happen is if the viewer perceives the object as rotating with the viewer. This improbable situation is in conflict with the tendency to see the central vertex as convex. In addition, normally, contours that are truly parallel to one another will converge in the retinal image with increasing distance. However, if the concave object is perceived as convex, the contours will seem to diverge in the retinal image with increasing distance. The only way this could occur with a convex object is if the sides were not parallel to one another (trapezoidal). Thus, in order to perceive the frame as convex, these cues must be overcome. In the binocular condition, disparity, convergence, motion parallax, and linear perspective information may specify the frame’s *actual* 3D structure. Therefore, we predicted that the participants would perceive the wire frame accurately, as concave, when viewing with two eyes.

### Methods

#### Participants

Participants included 21 college-aged adults. All adults were recruited from a university campus and had corrected-to-normal vision. Over 90% of participants were
of European American descent. All were treated according to the ethical guidelines set up by the American Psychological Association and University Institutional Review Board (IRB).

**Apparatus and stimuli**

The stimulus consisted of black rods, 6.35 mm in diameter, connected at the ends to form an empty wire frame. The overall shape of the frame was identical to the edges of a half-cube (see Figure 2A). In other words, the opposite edges of the frame were parallel to one another and the adjacent edges were perpendicular to one another. When the authors of the paper viewed the frame monocularly, they perceived it as convex and the sides were perceived as non-rectilinear or trapezoidal. This can be explained by the perception of the frame as convex (depth reversal) and the unchanged retinal image provided by the display. In other words, in order to perceive the farthest part of the display as the nearest part, the perception of shape is altered.

The wire frame was suspended from a horizontal bar that was 60 cm above the center of the frame. The frame was attached, at the highest point of the frame (seen in Figure 2A and Movie 1) to the horizontal bar above the display via a vertical rod so that it hung rigidly in front of the participant with the center vertex approximately aligned with the participant’s face.

A plain white sheet of foam core was placed approximately 60 cm behind the wire frame to provide a homogenous background. The 60-cm separation and the location of the light source (located overhead from the ceiling lights) ensured that the wire frame was seen against the homogenous background and the shadow of the wire frame was not cast on the white background. The frame was positioned so that the Y-shaped vertex pointed away from the viewer.

**Procedure**

After completing consent, participants were seated in a chair approximately 90 cm from the wire frame. An experimenter rotated the frame to present the central vertex as both convex and concave while the participant observed binocularly. Following a within-subjects design, participants completed 2 conditions with 6 trials per condition. Half of the participants received the monocular condition first, as a block of trials, and the other half received the binocular condition first. In each trial, participants were asked “does the middle point appear to be pointing out towards you or back away from you?” Between trials, participants were asked to look away from the display for a minimum of 2 s before continuing on to the next trial.

In the monocular condition, participants were asked to cover one eye with a hand. In the binocular condition, participants viewed the wire frame with both eyes. The binocular condition served to ensure that the participants’ responses were not the result of leading questions. In both conditions, participants were asked to move their heads from side to side to ensure that motion parallax information for the concave shape of the display was provided. The purpose of this was to ensure that the visual information provided to adults was as similar as possible to the infants’ experiences in Experiment 2.

**Results and discussion**

For each participant, we computed the percentage of trials in each condition in which the vertex was reported as convex. Each participant received two scores, one for each condition. Mean percentages are shown in Figure 3. A planned paired-samples t-test was conducted to compare the results from the monocular and binocular conditions. Participants perceived the frame as convex significantly more often in the monocular condition than in the binocular condition, \( t(20) = 3.798, p < 0.01 \).

These results cannot be explained by the nature of the questions we asked, because the demand characteristics in the monocular and binocular conditions were the same, while the reports of the participants were very different.

It is notable that the adult participants consistently perceived the wire frame as convex under monocular viewing conditions, despite having viewed it binocularly prior to the beginning of the experiment. Furthermore, participants rarely reported convexity in the binocular condition. This suggests that the wire frame was perceived accurately when binocular information was available and as convex when binocular information was not available. In addition, many of the participants spontaneously expressed surprise at the amount of depth experienced when viewing the display and that the display appeared to rotate to point at them as they moved side to side. This suggests that the Y-shaped center vertex of the frame...
was sufficient in providing a compelling illusion of 3D structure. Overall, these findings provide evidence that, in the absence of conflicting binocular information, line junction constraints on the possible interpretations of line junctions influence observers’ perceptions of ambiguous retinal images.

### Experiment 2

The goal of Experiment 2 was to examine if and when infants use line junction information to perceive depth in objects. Several previous studies have investigated this topic. Yonas and Arterberry (1994) investigated infants’ ability to discriminate edges from markings and found that 7.5- but not 5-month-old infants attended to lines indicating corners and edges more than to lines indicating markings. Furthermore, Kavsek (1999) found similar results using cylinders. These studies suggest that 7.5- and 8-month-old infants find the removal of a line that specifies object shape more salient than removal of lines that specify markings, but they fall short of demonstrating that 3D structure is perceived.

In two other studies, Bhatt et al. found that 3-month-old infants looked longer at a display that included an element that, to adults, appeared 3-dimensional on the basis of line junctions and “popped out” of the field. In addition, 3-month-olds did not show a looking preference in a control condition in which line junctions indicated that the target element was 2-dimensional (Bhatt & Bertin, 2001; Bhatt & Waters, 1998). These findings suggest that 3-month-old infants may respond to depth information provided by line junction cues. Shuwairi et al. found that when 4-month-old infants were presented with 2D pictures of possible and impossible cubes, they showed a looking preference for the impossible cube (Shuwairi, 2009; Shuwairi, Albert, & Johnson, 2007). Because line junctions provided information for the possible or impossible structure of the cubes, this finding suggests that infants may be sensitive to global shape as indicated by line junctions (Shuwairi, 2009; Shuwairi et al., 2007).

Together, these studies provide suggestive but not conclusive evidence that young infants use line junction information to perceive spatial layout. Infants as young as 3 to 4 months discriminate between displays in which line junctions provide information that objects are two- versus three-dimensional (Bhatt & Bertin, 2001; Bhatt & Waters, 1998) or that objects are possible or impossible (Shuwairi, 2009; Shuwairi et al., 2007). However, in the pop-out and impossible object studies, infants may have responded to low-level cues that correlated with 3D structure. Detection of 2D image cues, as Bhatt and Bertin (2001) and Bhatt and Waters (1998) pointed out, may represent an initial stage of development that occurs before 3D structure can be extracted.

In Experiment 2, we examined infants’ reaching, a spatial action, to the same stimulus under monocular and binocular viewing conditions. Using this method, image cues (the line junctions themselves) were equated in the two viewing conditions. The only thing we varied is whether the infant viewed the display monocularly or binocularly. As a result, this method controls for the possibility that infants could respond to differences in the proximal stimulus properties of the displays. If infants reach more toward the center of the display in the monocular condition as compared to the binocular condition, it would provide additional evidence that they use line junction information to perceive objects’ 3D structures.

We recorded infants’ reaching behavior toward the wire frame under monocular and binocular viewing conditions. A recent meta-analysis by Kavsek, Granrud, and Yonas (2009) found evidence that 5-month-old infants were sensitive to pictorial depth cues; however, the effects found for 7-month-olds were much stronger. Therefore, we tested 5- and 7-month-old infants to examine developmental changes in the sensitivity to line junction information for 3D structure. We expected that if infants perceive the wire frame as adults perceive it, they would reach to the central vertex of the display in the monocular condition but not the binocular condition. On the other hand, if infants do not extract depth from line junctions, we would expect them to reach more often to the edges of the wire frame in both the monocular and binocular conditions. If line junction cues are not used, reaches directed to the center in the monocular condition are unlikely because the area of the outer edges is much larger than that of the central area. In addition, linear perspective and motion parallax specify that the corners on the outer edge are closer than the central area.

### Methods

#### Participants

Participants included 47 infants: twenty-five 5-month-olds (12 males and 13 females; mean age = 157.72 days, age range = 150–169 days) and twenty-two 7-month-olds (9 males and 13 females; mean age = 224.36 days, age range = 210–236 days). Over 90% of the infants were of European American descent. In the 5-month group, 30 additional infants were excluded from data analyses due to fussiness (9), failure to reach a minimum of 6 times to the wire frame in each condition (17), or experimenter/equipment error (4). In the 7-month group, 11 additional infants were excluded from data analyses due to fussiness (6), failure to reach a minimum of 6 times to the wire frame in each condition (3), experimenter/equipment error (1), and bias to reach to the same location on all 12 trials (1). All infants and parents were treated according to the ethical guidelines set up by the American Psychological Association and University IRB.
Apparatus and stimuli

The display was identical to that used in Experiment 1. The only difference was that infants were seated on their parent’s lap on a chair with wheels that could be rolled toward the display.

Two digital video cameras were used to record reaching behavior toward the display. One camera was placed to the left of the display (from the infant’s perspective), perpendicular to the infant’s line of reaching. With this camera, we were able to record the location of reaching behavior from the side to differentiate a reach to the top, middle, or bottom of the display. A white sheet of poster board was placed opposite the camera and to the right of the infant to provide a homogenous background and increase contrast to make it easier to score the infants’ reaches. A second camera was directed downward from the ceiling directly above the wire frame. This camera was used to differentiate a reach to the left, middle, or right. A sheet of white poster board was placed on the floor to increase contrast in the recording taken from above. By viewing the infant from both recordings, behavior in all three axes of space could be scored.

Procedure

Upon entering the laboratory, experimenters explained the procedure to the parents before they read and signed the consent form. Parents sat facing the display on a chair with wheels and the infant sat on the parent’s lap. Parents viewed the display with two eyes and were not told the expected response of the infant to minimize the possibility that they could influence the infants’ reaching behavior. There were two conditions in the experiment, a condition in which the display was viewed monocularly and a condition in which it was viewed binocularly. In the monocular condition, an infant eye patch was carefully applied to the infant’s face such that it occluded all visual information to one eye only; the eye covered was randomly selected. Half of the subjects were randomly assigned to begin the study in the monocular condition and half to begin in the binocular condition. Six reaching trials in each condition were required for inclusion of the infant’s data in the study.

Each trial began with the infant approximately 90 cm from the center vertex of the display. At the beginning of each trial, the experimenter drew the infant’s attention to the wire frame by tapping the frame to make a noise and shaking the support system to make the display move slightly. Once the infant was fixated on the stimulus, the experimenter pushed the parent and infant toward the display until the infant was within reaching distance of the nearest point (approximately 30 cm). This distance allowed the infant to reach either toward the outer portions of the display or toward the center. Each trial ended once the infant reached toward the stimulus. If the infant did not reach toward the display, the infant and parent were brought back to the starting point, and the trial was restarted. This process was repeated until the infant completed a minimum of 6 monocular trials and 6 binocular trials. After the experiment, parents were debriefed and compensated for their time.

If an infant became fussy during the experiment, the parent and child took a break before continuing the experimental session. If an infant was too fussy to continue, the experiment was terminated.

To score reaching behavior, video recordings were transferred to a computer and analyzed in slow motion using iMovie. A preliminary scorer, blind to the locations of the infant’s reaches, determined whether a particular infant should be excluded from the sample based on number of reaches, fussiness, experimenter error, equipment error, etc. Another scorer, blind to condition, made a judgment of the goal of the infant’s reach in each trial. Scorers were made blind to condition by covering a portion of the computer screen to ensure that it was not possible to see whether or not the infant was wearing an eye patch. The scorer made a forced-choice judgment of whether the infant reached for the center vertex or the outer portion of the display. Movie 2, provided with this article, provides a visual example of infants reaching preferentially for the center and outer edges of the wire frame. If the infant reached with both hands, the experimenter scored the trajectory of the forward-most hand. Overall preference scores for each infant were determined by calculating the percentage of total reaches that were directed toward the center in each condition. A third experimenter scored a randomly selected subset of the videos to determine a measure of reliability, $r = 0.97$, $n = 10$.

Results and discussion

Figure 3 shows the mean percentage of reaches that were directed to the center of the display in each viewing condition for each age group. A 2 × 2 mixed ANOVA was conducted with age (5 months vs. 7 months) as a between-subjects factor and condition (monocular vs. binocular) as a within-subjects factor. The ANOVA revealed a significant main effect for condition, $F(1, 45) = 42.388, p < 0.001$; there was no significant main effect of age. The condition × age interaction was also not significant. These results indicate that infants in both age groups reached significantly more to the center region of the display in monocular trials than in binocular trials.

We also conducted planned one-sample $t$-tests to determine whether the infants directed significantly more than 50% of their reaches toward the center of the display in the monocular condition. The 5-month-olds reached to the center on 63.7% of the monocular trials, which was significantly greater than 50%, $t(24) = 3.29, p < 0.01$. The
7-month-olds reached to the center on 66.7% of the trials, which was also significantly greater than 50%, t(21) = 2.125, p < 0.05. Although we used 50% as the test value for these comparisons, the target area for a center reach was much smaller than the target area for an outer edge reach. Therefore, a 50% test value was very conservative.

In addition, in the binocular condition, infants’ reaches were directed toward the center of the display significantly less than chance. In other words, infants reached preferentially for the edges of the display more often than would be expected by chance when viewing with two eyes. This comparison was significant for the 5-month-old infants, t(24) = −7.473, p < 0.001, and marginally significant for the 7-month-old infants, t(21) = −2.035, p = 0.055.

The infants’ reaching preferences for the center of the wire frame suggests that both age groups perceived the frame as convex in the monocular condition. In the binocular condition, the infants’ reaching preference for the outer edges of the frame suggests that they perceived the wire frame as concave when it was viewed with two eyes.

An alternative interpretation of the results might be that the infants perceived the wire frame as flat, not convex, in the monocular condition. Evidence against this interpretation is provided by the observation that 16 of the older infants attempted to grasp the wire frame’s central vertex in front of the display in at least one trial. Only two of these infants attempted to grasp the vertex in the binocular trials. These grasp attempts strongly suggest that the frame’s central vertex was perceived as convex in the monocular condition.

The high attrition rate seen in the 5-month-old infants is worth noting. As many infants do not begin to reach until about 5 months of age, it is possible that some infants were not yet of reaching age at the time of their participation. Indeed, several of our 5-month-old infants did not reach for the wire frame at all. As 7-month-old infants are well within the age of reaching, we did not have this problem with this age group. It is possible that only the more developmentally advanced 5-month-old infants perceived the wire frame in the same way that 7-month-olds and adults do. Therefore, it is possible that we would find a developmental change in responsiveness to line junction information between non-reaching 5-month-olds and reaching 7-month-olds if we used a method that is not dependent on reaching. Nonetheless, high attrition rates are common among infant reaching studies, often nearing around 50% (e.g., Hemker, Granrud, Yonas, & Kavsek, 2010; Yonas, Cleaves, & Pettersen, 1978).

### General discussion

We examined the visual system’s use of line junction cues in the perception of 3D structure. In Experiment 1, we found that adults perceive a concave wire frame as convex when it is viewed monocularly. In Experiment 2, we investigated whether 5- and 7-month-old infants also perceive the center of the wire frame as convex. Both 5- and 7-month-old infants reached more to the center region of the display in the monocular condition than the binocular condition suggesting that they, like adults, perceived the wire frame as convex when binocular cues were eliminated.

The results of this study are consistent with previous findings that infants use constraints in other domains, including the perception of shape from shading (Granrud, Yonas, & Opland, 1985), perception of distance from linear perspective, and texture gradient cues (Arterberry, Yonas, & Bensen, 1989; Hemker et al., 2010; Yonas, Granrud, Arterberry, & Hanson, 1986). In addition, a recent study using a method similar to that used in Experiment 2 has shown that 6-month-old infants respond to the hollow face illusion. That is, infants perceive a concave mask as convex, demonstrating their use of the constraint that faces are convex or a general constraint that objects tend to be convex (Corrow, Granrud, Mathison, & Yonas, in press). This brings up the possibility that infants and adults may, in addition, use other constraints to interpret the internal Y-shaped vertex as convex (e.g., a general convexity assumption).

The finding that 5-month-old infants are sensitive to line junction information for depth is particularly interesting considering that most reaching studies investigating pictorial depth cues have found an increase in responsiveness to these cues between 5 and 7 months. However, the results of the present study are consistent with several recent reports that infants as young as 5 months of age respond to pictorial depth cues (Arterberry, 2008; Hemker et al., 2010; Kavsek et al., 2009).

Future work should examine whether the constraints used to perceive depth from line junctions and other depth cues are built-in or learned. Infants younger than 5 months of age were not tested in the present study due to limitations in their ability to reach. However, it is possible that younger infants would respond to line junction cues if different measures were used. With a sensitive enough measure, extremely young infants might demonstrate the use of line junction constraints to interpret an ambiguous 2D image on the retina. With the ability to test younger infants, we may be able to answer the central question of whether sensitivity to line junction information is learned over the history of the child or evolutionary history.

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