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Oculomotor Exploration of Impossible Figures in Early Infancy

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Previous studies have revealed that young infants can distinguish between displays of possible or impossible figures, which may require detection of inconsistent depth relations among local line junctions that disrupt global object configurations. Here, we used an eye-tracking paradigm to record eye movements in young infants during an object discrimination task with matched pairs of possible and impossible figures. Our goal was to identify differential patterns of oculomotor activity as infants viewed pictures of possible and impossible objects. We predicted that infants would actively attend to specific pictorial depth cues that denote shape (e.g., T-junctions), and in the context of an impossible figure that they would fixate to a greater extent in anomalous regions of the display relative to other parts. By the age of 4 months, infants fixated reliably longer overall on displays of impossible versus possible cubes, specifically within the critical region where the incompatible lines and irreconcilable depth relations were located, implying an early capacity for selective attention to critical line junction information and integration of local depth cues necessary to perceive object coherence.

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Perceiving objects and scenes as coherent in three dimensions (3D) is a fundamental ability of the visual system. In adults, object recognition and perception of 3D shape stem from extraction of critical information about the local spatial configuration of edges, junctions, binding contours, and surface characteristics (Biederman, 1987; Biederman & Ju, 1988; Enns, 1992; Hochberg, 1978; Marr & Nishihara, 1978). Here, we examine the mechanisms by which young infants analyze local pictorial depth information and integrate global spatial relations that lead to perception of coherent 3D objects.

Recent studies have used a looking-time paradigm to examine 4-month-olds' discrimination of possible and impossible cube displays (Shuwairi, 2009; Shuwairi, Albert, & Johnson, 2007; Figure 1) and have shown that infants look longer at pictures of impossible figures relative to their possible mates. The phenomenon of longer looking occurs in the context of a global structural incompatibility of the *critical region* with respect to other parts of the cube display. The critical region is defined as the central location in the stimulus with an arrangement of line junction cues (e.g., T-junctions denoting interposition) that specify the local depth order of bar surfaces. Line junction information in the critical region is either consistent or inconsistent in relation to the extended binding contours that terminate in arrow junctions (denoting corners) in the cube display. When the critical regions were

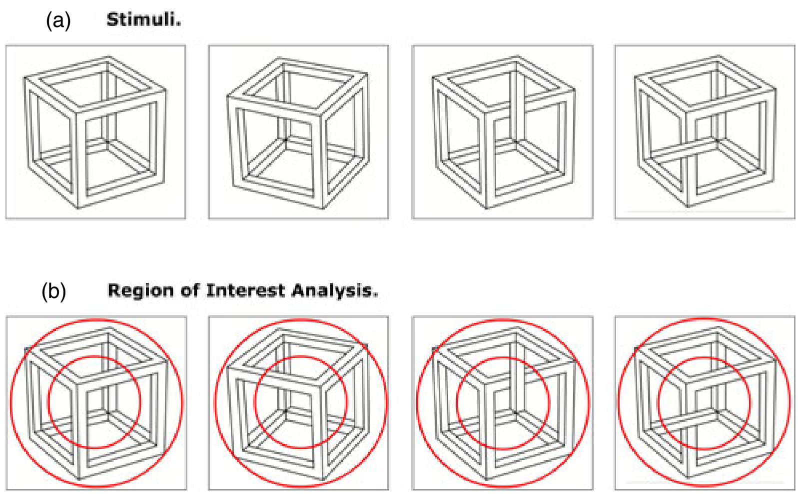

Figure 1 Schematic diagram of possible and impossible cube stimuli (top) and regions of analysis (bottom). The two cubes on the left are possible, and the two cubes on the right are impossible. The stimuli vary in their depth relations of two bar surfaces, defined by T-junctions that specify occlusion of the two surfaces in either a veridical, coherent fashion (e.g., possible cubes) or an anomalous, incoherent fashion (e.g., impossible cubes).

presented in isolation, that is, both of which are possible in the absence of extended binding edges and arrow junction contours, infants looked equally to the central critical regions of the possible and impossible cube displays (Shuwairi, 2009). Those results suggested an early ability to detect differences in local interposition cues denoted by T-junctions and to interpret local depth relations with respect to connectivity between T- and arrow junctions in the greater context of distinguishing between globally coherent ("possible") versus incoherent ("impossible") shapes.

Together these findings established that perceptual mechanisms involved in deriving 3D structural information from binding edges and critical line junctions in static images are available within the first few postnatal months, but left open the question of *how* infants are able to distinguish between pictures of possible and impossible objects. More specifically, are they engaging in increased visual exploration and more active comparison of local interior and exterior parts of the impossible figure? Perceiving global form inherently implies integration of local pictorial information and spatial relations among parts, and an important question awaiting clarification is whether infants 4 months of age and younger are actively registering the local line junction cues in the context of discriminating between possible and impossible objects.

The nature and development of coherent 3D object perception has long been a key topic in infancy research (Johnson, 2003; Kellman & Short, 1987; Piaget, 1954; Spelke, 1998). Young infants are sensitive to a number of visual cues needed to represent aspects of spatial orientation and object structure (Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Johnson, Slemmer, & Amso, 2004; Kellman & Spelke, 1983; Quinn, 1987; Quinn, Slater, Brown, & Hayes, 2001; Turati, Simion, & Zanon, 2003). Eye-tracking studies with 2- and 3-month-olds reveal rapid developments in performance in tasks of perceptual completion and visual search (Amso & Johnson, 2006; Johnson, Hall-Haro, Davidow, & Frank, 2008; Johnson et al., 2004), which may be due in part to enhanced information processing mechanisms that led to greater scanning efficiency and increased selective attention to relevant parts of object displays. Earlier work on the development of visual pattern perception showed that 3- and 4-month-old infants are sensitive to both local and global properties and that there is evidence of a global precedence effect (Ghim & Eimas, 1988). Those findings led us to predict that 4-month-olds would also show a pattern of increased visual scanning within the critical regions of impossible and possible cubes.

Prior research on the development of depth perception assessed infants' sensitivity to relative motion cues (e.g., Kellman, 1984; Kellman & Short, 1987; Kellman & Spelke, 1983) and evaluated sensitivity to pictorial depth cues using visually guided reaching tasks (Yonas, Elieff, & Arterberry, 2002). Both lines of research suggested that infants younger than 6 months show limited sensitivity to depth cues. Other studies demonstrated that 7-month-olds, but not younger infants, detected changes in line junction cues embedded in object displays (Kavsek, 1999; Yonas & Arterberry, 1994). More recently, however, a meta-analysis of reaching studies revealed that infants as young as 5 months also show appropriate visually guided reaching response to manipulations of depth cues, just as the 7-month-old infants do (Kavsek, Granrud, & Yonas, 2009), and 9-month-old infants were observed to direct more reaching behaviors (touching, scratching, rubbing, and patting) toward pictures of impossible cubes relative to possible cubes and control stimuli, implying that the infants found the unusual geometry unlike other objects previously encountered (Shuwairi, Tran, DeLoache, & Johnson, 2010).

Because 4-month-olds look longer at impossible versus possible cubes, and 3-month-olds exhibit sensitivity to both local and global depth information, we reasoned that young infants' visual scanning patterns, recorded with an eye-tracker, would be different when viewing line drawings of possible and impossible cubes. We hypothesized specifically that infants would selectively attend to line junction cues (e.g., T-junctions denoting interposition of surfaces) in critical regions of impossible cubes, where the structural anomaly occurs with respect to other parts of the object, relative to the analogous region of the possible figure (Figure 1b). If infants show increased fixation behavior toward the impossible versus possible cubes, we can infer that they detected the anomalous line junction cues present in an impossible figure and that they actively used this information to distinguish between pictures of structurally coherent and incoherent objects. These results, therefore, may provide insights into infants' ability to encode both local and global properties of shape as well as their ability to represent aspects of 3D objects given the available 2D pictorial information.

METHOD

Participants

Infant participants were selected from a public database of new parents and were recruited by letters and telephone calls. The final sample consisted of sixteen 4-month-olds (*M* age = 123.7 days, *SD* = 11.9; nine girls, seven boys) and eleven 2-month-olds (*M* age = 73.4 days, *SD* = 6.8; six girls, five boys). An additional ten infants were observed but not included in the final sample because of lack of attention or excessive fussiness (three 4-month-olds, one 2-month-old) and inability to attain a quality calibration needed to accurately record point of gaze (six 2-month-olds). All infants were full-term with no known developmental or visual difficulties.

Stimuli

Stimuli consisted of line drawings of possible and impossible cubes (see Figure 1a). The cube stimuli were drawn and animated using Flash (Adobe Systems, Inc., San Jose, CA) and presented as QuickTime AVI formatted movie files. Each of the cube stimulus images was approximately 11 × 11 cm in height and width, which subtended approximately 11° of visual angle. Between trials, infants viewed an on-screen "attention getter" animation (subtending 4° of visual angle) for approximately 3 sec to re-center their gaze and recapture their attention.

In each trial, infants viewed either a single possible cube or a single impossible cube. There were four stimulus displays: two different versions of the possible cube and two different versions of the impossible cube (Figure 1a). Cubes differed exclusively in the critical region (Figure 1b). With respect to all other regions of the figure, this particular spatial location is where the depth order of overlapping bar junctions of the cube made its global 3D structure either possible or impossible.

Possible and impossible displays were presented individually in a pseudo-randomized order, and each infant received a different stimulus order. Each of the four cube displays was presented individually for 10 sec, and each display appeared twice during the randomized sequence for a total of eight stimulus trials. No more than three of the same display type (possible or impossible) appeared consecutively. The order of the first stimulus in the sequence (possible versus impossible first) was counterbalanced across infants, and there were no reliable effects of stimulus order in preliminary statistical analyses.

Eye-tracking procedures

Infants sat in a quiet testing room approximately 57 cm away from the visual display. Infants' point of gaze was continuously recorded using a Tobii 1750 corneal reflection eye-tracker. Each infant underwent a five-point calibration routine to verify point of gaze. Fixations were recorded if the point of gaze was within 1° of visual angle for at least 30 msec. Stimulus displays were presented on the eye-tracking monitor using Clearview software (Tobii Technology, Inc., Falls Church, VA) .

Data analyses

The primary dependent measures were the means of the total accumulated duration of fixation times for each display type overall (possible versus impossible) and within the critical region (critical region possible versus critical region impossible) as well as the mean number of transitions between the critical region and other parts of the cube for each display type (possible versus impossible). For these analyses, the critical region was objectively defined as the central region of space in the cubes where the reversal of depth information occurred. The radius of the critical region measured approximately 2.5 cm, which amounts to 19.6 cm^2 of surface area (approximately 20% of the entire cube display). The mean duration of fixation time was computed by averaging across the four test trials for each display type (possible versus impossible) for each infant (cf. Salapatek, 1968). Statistical analyses included a 2×2 repeated-measures ANOVA (Age: 2-month versus 4-month $\times$ Display: possible versus impossible) for the entire cube display and within the critical region of each display. Planned comparisons (*t*-tests) were also conducted to evaluate *a priori* hypotheses. And an *impossible preference score* was calculated as the sum of fixation time for the impossible cube divided by the sum of fixation times for both the possible and impossible cubes, with a score of .50 representing no preference (i.e., 50/50 chance). All tests of statistical significance used an alpha level of .05, and all *t*-tests were two-tailed.

For inclusion in the final sample, infants were required to have a good-quality calibration and contribute a minimum accumulated fixation time of at least 2 sec on three of four trials for each display type. All but one 2-month-old infant provided data on all 4 trials of each type to these analyses.

RESULTS

Analysis of fixation behaviors on whole display

There was a main effect of display, $F(1, 25) = 7.27, p = .01$ (power = .74, partial $\eta^2 = .23$, $d = .234$), and there were no interactions. Although the interaction between age and display type was not significant, we tested our a priori predictions that younger and older infants would show different preference patterns by conducting separate *t*-tests at each age comparing infants' looking to the impossible and possible cubes. Among the 4-month-olds, the mean duration of fixation time was significantly larger toward the impossible relative to the possible cube ($M_{\text{Possible}} = 4.4$ sec, $SE = .52$, $M_{\text{Impossible}} = 4.9$ sec, $SE = .49$, $t(15) = 2.73$, $p < .01$, $d = .277$). However, the pattern of behavior did not achieve statistical significance among the 2-month-olds ($M_{\text{Possible}} = 5.4$ sec, $SE = .58$, $M_{\text{Impossible}} = 5.8$ sec, $SE = .53$, $t(10) = 1.18$, $p > .20$, $d = .173$).

A majority of infants also initiated a significantly greater number of transitions back and forth between the critical region and other areas of the display when viewing the impossible cube relative to the possible one,

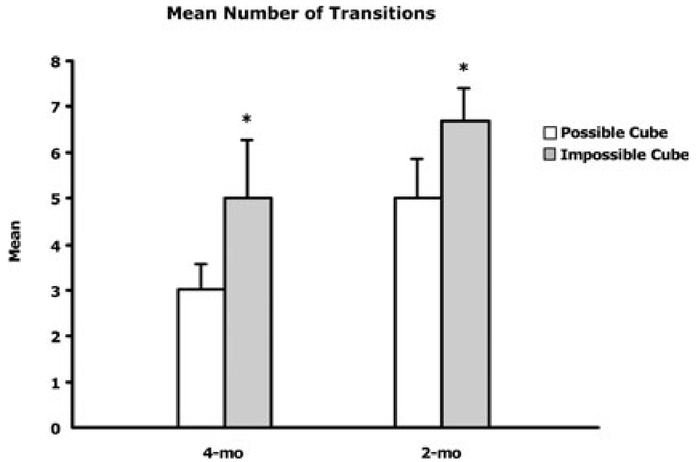

Figure 2 Mean number of oculomotor transitions initiated back and forth between the interior critical region and other parts of the possible and impossible cube for each age-group. Error bars reflect standard error of the mean.

$F(1, 25) = 8.79$, $p = .007$ (power = .81, partial $\eta^2 = .26$, $d = .551$; see Figure 2). The pattern of increased scanning activity (i.e., oculomotor transitions) evoked by the impossible figure was observed in 14 of the sixteen 4-month-olds ($M_{\text{Possible}} = 3$, $SE = .49$, $M_{\text{Impossible}} = 5$, $SE = 1.24$, $t(15) = 2.30$, $p < .04$, $Z = 2.74$, $p = .006$, $d = .525$), and a statistical trend for this pattern of activity was also observed in eight of the eleven 2-month-olds ($M_{\text{Possible}} = 5$, $SE = .78$, $M_{\text{Impossible}} = 6.7$, $SE = .70$, $t(10) = 2.13$, $p < .06$, $d = .675$, $Z = 1.87$, $p = .06$).

The 4-month-old infants' mean impossible preference score was .54 ($SE = .015$), and this differed significantly from chance, $t(15) = 2.57$, $p < .02$. For 4-month-old infants, the pattern of increased fixation time on the impossible cubes relative to possible ones was observed in 12 of 16 infants, $Z = 2.53$, $p < .01$. The mean impossible preference score for 2-month-olds was .518 ($SE = .012$), which was not reliably different from chance (.50), $t(10) = 1.51$, $p > .10$ (n.s.), and only six of the eleven 2-month-olds showed greater fixation time to the impossible cubes, $Z = 1.11$, $p > .20$ (n.s.).

Analysis of fixation behaviors within critical region

Infants generally initiated a greater duration of fixation time within the critical region of the impossible cubes relative to the same defined area of interest within the possible cubes, $F(1, 25) = 3.53$, $p < .07$ (power = .44, partial $\eta^2 = .13$, $d = .215$). This pattern of results was significant among the 4-month-old infants who fixated for an average of approximately half a second longer within the critical region of the impossible cubes relative to the critical region of possible ones, $M_{Possible} = 3.3$ sec, $SE = .42$, $M_{Impossible} = 3.8$ sec, $SE = .47$, $t(15) = 2.96$, $p < .01$, $d = .322$, and this difference was reliably greater than chance, $t(15) = 2.12$, $p < .05$. By contrast, the 2-month-olds showed no reliable differences in fixation time within the critical region of the possible versus impossible display ($M_{Possible} = 3.6$ sec, $SE = .49$, $M_{Impossible} = 3.7$ sec, $SE = .53$, $t(10) = .24$, $p > .80$, $d = .04$).

The 4-month-old infants' mean impossible preference score within the critical region was .54 ($SE = .019$), which differed significantly from chance, $t(15) = 2.12$, $p < .05$, and this preference for the critical region of the impossible cube was observed in 12 of the 16 infants ($Z = 2.53$, $p < .01$). The 2-month-old infants' mean impossible preference score within the critical region was .50 ($SE = .022$), and this did not differ from chance, $t(10) < .01$, $p > .90$.

DISCUSSION

We asked whether 2- and 4-month-old infants would engage a differential pattern of oculomotor exploration as they viewed pictures of possible and impossible cubes. The 4-month-old infants fixated reliably longer on pictures of impossible cubes relative to possible ones, which replicated results of previous looking-time studies (Shuwairi et al., 2007; Shuwairi, 2009). Both the 2- and 4-month-olds responded with increased scanning activity (e.g., transitioning back and forth) between the critical region and other parts of the display when viewing the impossible cube relative to possible one. However, only the 4-month-olds also allocated a reliably greater degree of selective looking within the critical region where the anomalous depth relations occur in the impossible figure, and they appeared to more actively explore this region relative to other parts of the display, likely driving the overall effect. This pattern of behavior may be indicative of infants' ability to register illogical line junction cues present in the depicted object as well as their attempts to reconcile the depth order information and spatial relations with respect to the other connected parts of the object (i.e., T-junctions of the bars in the critical region and arrow junctions at their terminal corners).

While we may have begun to observe inklings of increased overall fixation time and scanning activity (i.e., transitions) toward the impossible cubes in some of the 2-month-olds, the younger infants did not show statistically reliable differences in selective looking within the critical region of the impossible cubes. At this point, our conclusions from the 2-month-olds are only speculative, given the small sample size, low power, and lack of statistical difference from the 4-month-old infants. Perhaps using larger samples and providing the younger infants with additional viewing time to process the object contours, or presenting test trials in a more predictable (i.e., A-B-A-B) sequence – as in our previous looking-time studies – rather than in a randomized order, we could empirically evaluate further these potential differences in perceptual performance of 2-month-olds relative to 4-month-olds.

Selective attention to specific local depth cues and the fundamental relations among parts of an object appear to be available to infants within the first few months of postnatal development. The observed increase in oculomotor exploration initiated toward the impossible figures may reflect the 4-month-old infants' attempts to reconcile the local parts of each cube and efforts to discern the potential differences between the depicted objects. Between 2 and 4 months, visual exploration becomes more refined in terms of the infant's ability to register and encode relevant features and integrate line junction cues, and our results provide further evidence that these behaviors become more selective by the age of 4 months.

These results demonstrate that by the age of 4 months, the infant visual system is capable of detecting critical line junction cues and shape-defining contours, evaluating local depth order of surfaces, and integrating spatial relations among parts in order to differentiate between structurally matched pairs of possible and impossible cubes. Our data further corroborate a recent meta-analysis of earlier reaching studies, revealing that sensitivity to depth cues and recognition of objects in three dimensions may be functional earlier in development than reaching paradigms with older infants had previously suggested (Kavsek et al., 2009).

Young infants become increasingly more accurate and consistent in directing their gaze and selectively scanning relevant contours and features of objects, which coincides with ongoing improvements in object perception skills (Bronson, 1990; Johnson et al., 2004). Given that the 2-month-olds in our study did not show a reliable preference for the impossible cube or for the critical region of the impossible cube relative to the possible one, it is reasonable to speculate that some of the infants in this age-group might not have been able to locate the critical junction of the display, which happens to be within the center of the cube. Perhaps complex geometric stimuli, such as the cubes used in our experiment, require a greater amount of viewing time in order for younger infants to locate the center of the stimulus and fully examine all parts of the display.

The task of possible and impossible object discrimination inherently involves selectively attending to relevant parts, analyzing the interior and exterior contours, and integrating the available spatial and pictorial cues. By

4 months, infants demonstrate the ability to detect relevant local pictorial depth cues present in 2D images and extract critical information for perceiving global 3D structure.

Our results may seem surprising because earlier work suggested that school-aged children had difficulty with various verbal and motor tasks including same–different comparisons, freehand drawing from memory, and attempting to build possible and impossible figures from pieces of wood (Enns & King, 1990; Young & Deregowski, 1981). It is conceivable that those tasks involved a larger degree of cognitive, verbal, and motor demands placed on the children during the experiment, or perhaps those measures did not directly assess the perceptual mechanisms responsible for discriminating the stimuli. It is also possible that choice of stimuli may have played a role in yielding these particular results. For example, the stimuli used by Kavsek (1999) included curved line segments and line drawings of cylindrical objects, and he reported that sensitivity to line junction cues denoting shape emerges by 7 months. However, it may be the case that sensitivity to curvilinear information develops after an initial sensitivity to straight-edge contours and angular vertices (e.g., T-, Y-, and L-junctions), which emerges earlier at approximately 3 months of age (Bhatt & Bertin, 2001; Bhatt & Waters, 1998).

Studies of picture processing and change detection in adults have shown that observers rapidly detect a different or changed part of the display (Hochberg, 1978, 1980; Parker, 1978; Zelinsky, 2001). Longer fixation periods or aberrant patterns of fixation behavior may be indicative of detecting inconsistent information that does not agree with existing expectations or internal representation of objects and scenes (Parker, 1978). Although many studies show that infants typically look longer at novel objects and unusual or unexpected events, we are aware of no published reports of infants' oculomotor responses to actual displays of physically impossible objects relative to possible ones.

These data are the first to reveal that 4-month-olds (a) selectively attend to critical line junction cues and local pictorial depth information present in static images and (b) actively use this information to identify contradictory spatial relations that ultimately render a depicted object impossible in 3D space. By the age of 4 months, therefore, infants demonstrate an early capacity to detect conflicting local line junction cues and they can use that information in the broader context of interpreting global 3D shape and judging structural possibility. These findings help to further clarify the nature and development of object perception and inform our understanding of the mechanisms supporting infants' ability to represent global shape and interpret objects, both real and depicted, in the world as coherent in three dimensions.

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