

The hollow-face illusion in infancy: do infants see a screen based rotating hollow mask as hollow?

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Abstract. We investigated whether infants experience the hollow-face illusion using a screen-based presentation of a rotating hollow mask. In experiment 1 we examined preferential looking between rotating convex and concave faces. Adults looked more at the concave—illusory convex—face which appears to counter rotate. Infants of 7- to 8-month-old infants preferred the convex face, and 5- to 6-month-olds showed no preference. While older infants discriminate, their preference differed from that of adults possibly because they don't experience the illusion or counter rotation. In experiment 2 we tested preference in 7- to 8-month-olds for angled convex and concave static faces both before and after habituation to the stimuli shown in experiment 1. The infants showed a novelty preference for the static shape opposite to the habituation stimulus, together with a general preference for the static convex face. This shows that they discriminate between convex and concave faces and that habituation to either transfers across a change in view. Seven- to eight-month-olds have been shown to discriminate direction of rigid rotation on the basis of perspective changes. Our results suggest that this, perhaps together with a weaker bias to perceive faces as convex, allows these infants to see the screen-based hollow face as hollow even though adults perceive it as convex.

Keywords: Hollow-face illusion, infants, face perception, depth perception, convexity preference.

1 Introduction

The hollow-face illusion is the phenomenon of a concave face or mask being perceived as a normal, convex face (Gregory 1970). In this study we investigated whether infants, like adults, experience the illusion.

The hollow-face illusion is a powerful and striking illusion in adults. We consistently perceive the incorrect convex alternative even when potentially unambiguous cues to depth, including stereoscopic disparities and parallax resulting from self-motion, are available and we are fully aware of the true shape of the mask. In adults this has been attributed to our past experience with, and knowledge of, faces as convex three-dimensional surfaces with noses that stick out rather than in (Gregory 1997) and a general convexity bias for any objects (Hill

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and Bruce 1993, 1994; Johnston et al 1992; Kleffner and Ramachandran 1992; Langer and Bülthoff 2001). Our aim here is to ask whether infants, with considerably less experience of the world, also misperceive a concave mask as a convex face.

In the experiments reported here we used screen-based presentation of a computer-generated hollow face. Both the convex and the concave faces used were attached to a block (see figure 1). When the hollow version is shown rotating from left to right adults have the striking impression that the illusory convex face and the block appear to rotate in opposite directions and with the face rotating twice as fast (Gregory 1970). This is very different from the rotation of the actual convex face which rotates in time with and in the same direction as the block. We thought that infants might, like adults, find the unusual movement of the concave version interesting and preferentially look at it if, and only if, they are experiencing the illusion.

Shading both defines the face and is responsible for the ambiguity that allows the concave surface to be seen as convex. This is because any pattern of shading is ambiguous and could have resulted from either a convex or a concave surface. These interpretations are normally associated with opposite lighting directions, and there is a bias towards the percept consistent with lighting from above. Here lighting was along the line of sight and would not have biased either percept. The perceived counter rotation of the concave face in adults is also consistent with the changes in shading that would be produced by a convex face rotating in the opposite direction to the block.

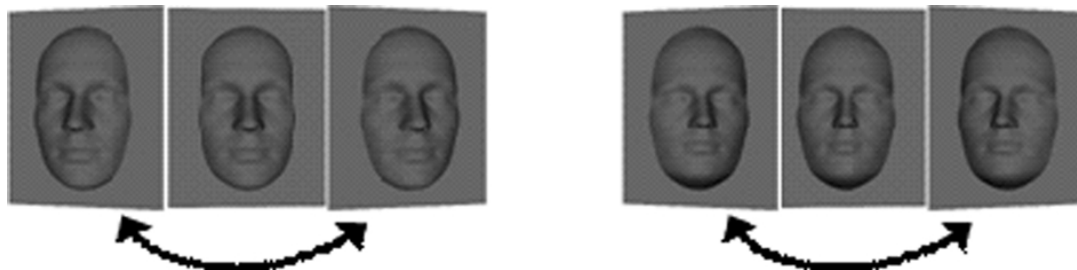


Figure 1. The rotating convex face (left) and concave face (right) which were used as the stimuli. The face oscillated 10 deg. from left to right around the vertical axis. In experiment 1 the rotating convex and concave faces were presented side by side on a CRT monitor. In the habituation phase in experiment 2 one rotating convex face or one rotating concave face was presented on the centre of a CRT monitor. The rotating animations used are provided as a [supplement](#).

To disambiguate the perceived shape and the direction of the motion, one must combine contours, perspective, and motion as depth cues. Contours define the block and, together with perspective, indicate orientation in angled views (figure 1). While structure-from-motion itself is ambiguous when the object rather than the observer moves (Ulman 1979), the effects of perspective on the block disambiguate its motion. Therefore, when seen in motion, changes in perspective could disambiguate the perceived direction of motion of the block. Motion associated with the face then has the potential to specify whether it is convex or concave, assuming it is rigidly connected to the block.

The infants participating in these experiments ranged from 5- to 8-months old. Previous studies have shown that infants as young as 4 months can perceive depth from kinetic information (Arterberry and Yonas 1988) and that infants of this age, like adults, have a bias to assume rigidity when interpreting such motion (Kellman et al 1986). However, only infants around 7 months show evidence of perceiving depth from pictorial depth cues such as shading (Granrud et al 1985; Imura et al 2008; Tsuruhara et al 2009, 2010) or perspective (Yonas et al 1978). Perspective combined with motion determines perceived direction of

object movement also in 7-month-olds (Oross et al 1987). Considering these previous results, one can determine it is possible that depth perception is sufficiently developed by the age of 8 months for infants to process the depth information available similar to the way adults do. The development in depth perception would be expected to affect how the stimuli are perceived.

Studies of the hollow-face illusion in adults often ask participants to indicate a change in their perception between convex and concave (Hill and Bruce 1993, 1994; Hill and Johnston 2007; Papathomas and Bono 2004), but this is clearly not possible with infants. Here we instead made use of the preferential-looking- and habituation-novelty-based paradigms commonly used with infants. In experiment 1 we tested for preferential looking between convex and concave rotating faces attached to a block. In experiment 2 infants habituated to the same stimuli which were presented in experiment 1 and then tested their novelty preference for convex as compared with concave static faces.

2 Experiment 1

In this experiment we tested both infants' and adults' preferential looking at rotating convex and concave faces attached to a block. This tested whether infants perceive the hollow-face illusion in the same way as adults do. In adults we anticipated a preference for the unusual and striking counter rotation associated with the illusory perception of the hollow face as convex. Infant participants were split into two groups of 5- to 6-month-olds and 7- to 8-month-olds as we expected the development of depth perception between these ages could affect perception of the stimuli.

2.1 Method

2.1.1 Participants. The final sample in the experiment consisted of 10 adults aged in their twenties and thirties (2 females and 8 males), 10 five- to six-month-old infants (5 females and 5 males), and 10 seven- to eight-month-old infants (6 females and 4 males). The mean age of the younger infants was 179.3 days ($SE = 4.7$ days) and that of the older infants was 220.2 days ($SE = 3.3$ days). An additional three infants were tested but were excluded from the analysis because of fussiness (one) or total looking times during the two trials that were less than 20 seconds (two).

2.1.2 Stimuli. Figure 1 shows the stimuli used in this experiment. The stimuli were based on a three-dimensional head model derived from 100 male and 100 female Caucasian faces (Vetter and Troje 1997). The head model was combined with a 20 cm (width) \times 25 cm (height) \times 12 cm (depth) block in Autodesk Maya Version 5, using the Boolean Difference Operator to make the hollow mask and the Boolean Union Operator to make the convex face. The face itself was 13 cm (width) \times 21 cm (height) \times 6 cm (depth). The resulting models were rendered in the software using a modelled 35 mm camera 55 cm in front of the face. Lighting was from a directional light shining along the line of sight. Phong rendering was used, and both face and block were assigned the same mid grey Lambertian reflectance. A sequence of images was rendered of the face/block combination rotating in 1-deg. steps from -10 deg. to $+10$ deg. (0 deg. indicates frontal view). These were combined into animations showing the faces oscillating back and forth at 30 frames per second. One complete loop had a duration of 1.4 seconds. The stimuli were presented on a computer monitor so that these did not have stereo information. The actual size of each face on the screen was 15.6 cm (width) \times 18.8 cm (height).

2.1.3 Apparatus and procedure. The same apparatus and settings were used for both adult and infant participants. All stimuli were presented on a 22-inch CRT monitor (Mitsubishi

DP2070SB or Totoku-Calix CDT2141). The distance from the centre of the CRT monitor to each participant's eyes was maintained at approximately 40 cm. The participant and the monitor were located inside an enclosure made of iron poles. A black cloth surrounded the monitor, and the room was kept dark during the trials so that the edge of the screen was not clearly visible. The width and height of the screen were 40 cm and 30 cm, respectively. The resolution of the screen was set at 1024 × 768 pixels. There were two loudspeakers, one on either side of the monitor. A CCD camera, located just below the monitor, was used to videotape the infant's behaviour throughout the experiment. The experimenter observed the participant's behaviour via a TV monitor connected to the camera.

In the experiment with adults participants sat in front of a 22-inch CRT monitor. They were instructed to look at a pair of rotating images of convex and concave faces and to look at the face that seemed more interesting for as long as they could. The stimuli were presented for 20 seconds each. The positions (left/right) of the two faces were counterbalanced across participants. After viewing the faces, participants wrote down the location of the stimulus at which they looked longer, left or right, and the reasons why they found the stimulus interesting.

In the experiment with infant participants a preferential-looking paradigm was used. During the experimental trials each infant sat on his or her parent's lap in front of the CRT monitor. Prior to each trial a fixation figure, accompanied by a short sound, was presented at the centre of the monitor. When the infant looked at the fixation figure, the experimenter initiated the trial. The fixation figure disappeared, and a pair of rotating images, one convex and one concave, was presented. Each infant took part in two 20-second trials. The presentation time of the stimuli was fixed at 20 seconds for each trial, regardless of whether the infant did or did not look. The positions (left/right) of the two faces were counterbalanced across participants on the first test trial and reversed on the second trial.

2.1.4 Data coding and analysis. One observer, who was unaware of the stimulus identity, measured each participant's fixations to the left and right sides of the monitor from video recordings. Only the participant's looking behaviour was visible in the video.

As an index of the relative amount of looking time at the concave face compared with the convex face, a *concave preference score* was calculated for each participant. This was the participant's looking time to the concave stimulus divided by their total looking time for either of the stimuli (ie, stimulus duration with time not looking at the screen subtracted).

2.2 Results

The adult participants all looked at the screen for as long as the stimuli were presented. The mean concave preference score was 0.70 ($SE = 0.07$). To examine whether the preferences differed significantly from chance (0.5), a two-tailed one-sample *t*-test was conducted on the preference. The *t*-test showed that adults' preference for the concave face was significantly above chance [$t(9) = 3.03, p < 0.05$]. After the experiment the adult participants reported that both of the faces appeared to be convex, but that one face appeared to rotate in the opposite direction to its background while the other appeared to rotate in the same direction as its background. They also reported looking longer at the former, as it was the more interesting.

For infants looking times on all trials were combined. We excluded infants with combined looking times of less than 20 seconds. The mean total looking times were 31.04 seconds ($SE = 1.73$) for the younger group and 30.27 seconds ($SE = 1.09$) for the older group. A two-tailed *t*-test showed no significant difference in the total looking times between groups [$t(9) = 0.73, ns$]. Thus any difference in the preference scores for the two age groups cannot be the result of a difference in total looking time. The mean concave preference scores were 0.47 ($SE = 0.02$) for the younger group and 0.42 ($SE = 0.02$) for the older group. These scores were compared with chance (0.5) through the use of two-tailed one-sample *t*-tests. The *t*-tests

showed that the older infants significantly preferred the convex face [$t(9) = 3.46, p < 0.01$] whereas the younger infants' preference was not different from chance [$t(9) = 1.85, ns$].

2.3 Discussion

In experiment 1 we compared infants' and adults' relative looking preferences for rotating convex and concave faces shown side by side. With the stimuli used, when the concave face is seen as convex, it appears to rotate in the opposite direction of its background (Gregory 1970). As such movement is unusual, we expected that if the hollow-face illusion was perceived by the infants as it is by adults, then both groups would look at the concave face for longer than the convex face.

The results revealed that adults did show the expected preference, but infants aged 7 to 8 months showed the opposite preference while infants aged 5 to 6 months showed no significant preference. This clearly demonstrates different looking preferences in infants' and adults and suggests that they experience the stimuli differently.

The difference between the younger and the older infants might be explained by the development of depth perception over this period. Although younger infants have been shown to recover depth from kinetic information (Arterberry and Yonas 1988), the perception of shape from shading is not expected to have occurred in the younger group of infants (Granrud et al 1985; Imura et al 2008; Tsuruhara et al 2009, 2010). The younger infants did not show a clear preference for one rotating block over the other, suggesting that their perception of the convex face and that of the concave face were not dramatically different: in particular, it appears they did not experience counter rotation of the concave stimuli.

Perception of shape from shading has previously been shown to be sufficiently developed in the older group, but they showed the opposite preference to that of adults. There are at least two possible explanations for this. The first explanation is that if the older infants perceive the actual three-dimensional structure of the stimuli—that is, the convex faces as convex and the concave face as concave—they may regard only the convex face as a face. Given infants are known to look longer at face-like objects (Fantz 1963), this would then explain the convex preference found. However, it begs the question as to *how* the older infants can see the hollow face as hollow given that this does not seem possible for adults. Motion parallax does provide a potentially disambiguating cue to structure. While structure-from-motion itself is ambiguous when the object rather than the observer moves (Ulman 1979), the effects of perspective on the block disambiguate its direction of rotation. Perspective combined with motion can determine perceived direction of rotation in 7-month-olds (Oross et al 1987). The motion of the face then has the potential to specify whether it is convex or concave, providing it is assumed to be rigidly connected to the block. An alternative explanation is that the 7- to 8-month-olds experience the illusion and the related counter rotation but find the counter rotation disturbing or unpleasant and look away from it. Experiment 2 provides a further test of whether the older infants are seeing the hollow face as convex or concave.

3 Experiment 2

In experiment 2 we investigated whether infants aged 7 to 8 months perceive the concave face as concave or as convex using the habituation-novelty preference procedure. This involved testing the infants' relative preference for static convex faces as compared with concave faces both before and after habituation to the same two types of rotating stimuli shown in experiment 1. The test stimuli (see figure 2) showed a 65-deg. view outside the range used to construct the rotating sequences. The additional occlusion cues provided make this stimulus much less ambiguous with respect to convexity/concavity—it is clear which one is 'sticking out'.

If 7- to 8-month-old infants do not experience the illusion when habituating to the concave face rotating, they would be expected to show a novelty preference to the static convex face. If they do experience the illusion as a convex face sticking out from the block, then a novelty preference will be for the static concave test stimulus. We also could expect a preference for the concave test stimulus after habituating to the genuinely convex face.

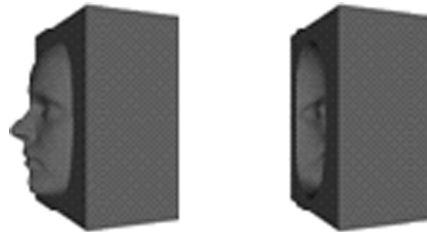


Figure 2. Static 65-deg. views of the convex face (left) and concave face (right) presented side-by-side for pretest and posttest trials during experiment 2.

3.1 Method

3.1.1 Participants. The final sample in the experiment consisted of 24 seven- to eight-month-old infants (11 females and 13 males), and the mean age was 226.2 days ($SE = 3.9$ days). Data from an additional 12 infants were excluded based on their looking times: a combined looking time of less than 8 seconds in the two pretest trials or in the two posttest trials (six) or longer combined looking times in the last two habituation trials than in the first two (six). Note that the looking times in the last two habituation trials were expected to be shorter than those in the first two habituation trials if the infants were habituated. Data from one infant were also excluded with the criteria of the side bias more than 90 % of the total looking time.

3.1.2 Stimuli, apparatus, and procedure. We used a habituation-novelty preference procedure consisting of three phases: prehabituation test, habituation, and posthabituation test. In the first phase infants were presented with two 10-second pretest trials in which static profiles of a convex and a concave face were presented side by side (figure 2). The infants then were shown four 20-second habituation trials in which either a rotating convex or a rotating concave face was presented. The rotating faces were the same as in experiment 1. The habituation phase was immediately followed by two 10-second posthabituation test trials. The prehabituation and posthabituation test trials were identical, allowing us to compare each infant's preferential looking before and after the habituation. Infants are known to look longer at novel objects than habituated ones (Fantz 1964). A novelty preference (looking longer at a concave profile after habituating to a rotating convex face and vice versa) indicates that infants have discriminated between the two stimuli, in this case the rotating convex and concave faces, and differentially associate them with the two posttest stimuli. Twelve infants were randomly assigned to each of two habituation display conditions, one showing a rotating convex face and the other a rotating concave face.

The profiles presented in the pretests and posttests were made from the same materials as used to make the stimuli used for both experiment 1 and the habituation phase. However, rather than a sequence of images, they consisted of a single image of the face stimuli viewed from 65 deg. to the side (figure 2).

Other methodological details were the same as for experiment 1.

3.1.3 Data coding and analysis. One observer, who was unaware of the stimulus identity, measured each infant's fixations to the left and right sides of the monitor from video recordings. Only the infant's looking behaviour was visible in the video.

As an index of the relative amount of looking time at the concave face compared with the convex face, a *convex preference score* was calculated for each participant. This was the participant's looking time to the convex stimulus divided by their total looking time to either of the stimuli (ie, stimulus duration with time not looking at the screen subtracted). In addition, as an index of whether infants looked longer at the novel face, we also calculated a *novelty preference score* for each infant in the pretests and the posthabituation tests. Hereafter 'novel shape' in pretests as well as posttests indicates the face not presented in the habituation phase. This was done by dividing the infant's looking time to the novel face by the total looking time separately for each phase.

3.2 Results and discussion

For the habituation phase individual looking times were averaged across the first two and the last two trials (table 1). We excluded infants who showed longer combined looking times in the last two habituation trials than in the first two. To confirm that the infants habituated to the displays, a 2×2 ANOVA was performed on the looking times with: (i) the trial (the first two, the last two) as a within participants factor and (ii) the types of the habituation displays (convex, concave) as a between participants factor. The ANOVA revealed a significant decrease in looking times over trials [$F(1,22) = 56.47, p < 0.01$]. The main effects of the habituation display type [$F(1,22) = 3.17, ns$] and the interaction [$F(1,22) = 0.18, ns$] were not significant. This demonstrates that habituation occurred and was not dependent on the type of stimulus.

Table 1. Mean looking time (seconds) and standard errors (in parentheses) during the habituation trials in experiment 2. The individual looking times were averaged across the first two and the last two trials.

Habituation trials	First two	Last two
Habituated face		
Convex	25.5 (1.9)	20.4 (2.2)
Concave	26.1 (1.4)	17.6 (1.7)

Figure 3 shows mean convex preference scores. The pretests and the posthabituation test difference is consistent with a novelty preference, as infants' preference after habituation was towards the novel profile. This novelty preference indicates that infants aged 7 to 8 months both discriminated between convex and concave faces and that this discrimination transferred across a large change in view and from moving to static stimuli. The novelty preference is also consistent with infants having perceived the convex face as convex and the concave face as concave when rotating. To examine this novelty preference, a 2×2 ANOVA was performed on the novelty preference scores with: (i) Test (pre, post) as a within participants factor and (ii) the type of the habituation displays (convex, concave) as a between participants factor. The ANOVA revealed significant main effects of Test [$F(1,22) = 6.64, p < 0.025$], indicating that the infants showed a novelty preference. Type of habituation display [$F(1,22) = 11.23, p < 0.01$] was also significant, but no significant interaction [$F(1,22) = 0.55, ns$] was found.

Given the preference for the convex face shown in experiment 1, the significant main effect of habituation display in this experiment may suggest a general preference for the convex test stimulus. To analyse any spontaneous convexity preference in the case of the static test stimuli, we conducted a two-tailed two-sample *t*-test on a convex preference score for the pretests. The *t*-test showed no significant difference in convexity preference between habituation conditions pretest [$t(22) = 0.58, ns$]. Therefore, we combined the pretest convexity preference scores for both habituation conditions. A two-tailed one-sample *t*-test

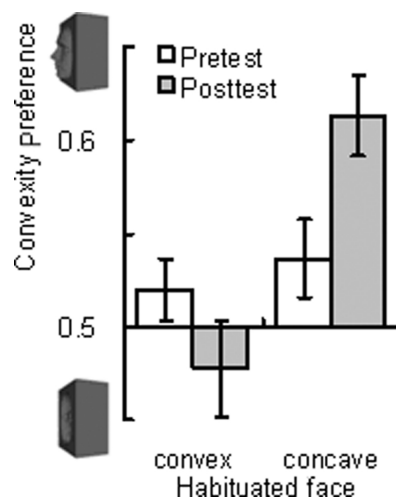


Figure 3. Mean convex preference scores pretest and posttest in both experiment 2 habituation conditions. Error bars indicate standard errors. Please note that an increase in the convexity preference score indicates a novelty preference for the concave habituation condition while the opposite is true for the convex habituation condition (and novelty preference = 1 – convexity preference).

comparing the combined convexity-preference scores to chance (0.5) showed a marginally significant convexity preference overall [$t(23) = 2.04, p = 0.053$]. This may be because only the profile of the convex face was seen as a face or just because it is the larger stimulus (Fantz and Fagan 1975). The reason for the general preference to the static convex test face cannot be determined from this experiment; the key finding is the novelty preference, which suggests that infants aged 7 to 8 months discriminated between convex and concave faces.

4 General discussion

In this study we investigated whether there is evidence of the hollow-face illusion in infants as well as in adults. In Experiment 1 we compared infants' and adults' looking preferences between rotating convex and concave faces and found opposite preferences between adults and 7- to 8-month-old infants, but no preference in 5- to 6-month-olds. In experiment 2 we tested whether 7- to 8-month-old infants regard the rotating convex face as convex and the concave face as concave using the habituation-novelty preference paradigm. The results showed a novelty preference together with a general preference for the static convex test stimulus.

The results of experiment 1 showed that adults looked longer at the concave face than the convex face as predicted, but that infants aged 7 to 8 months showed the opposite preference. The convexity preference in 7- to 8-month-olds suggests that they may not experience the 'impossible' counter rotation that adults comment upon, instead perceiving concave as concave and convex as convex and preferring the latter more face-like stimulus (Fantz 1963). An alternative explanation is that infants experience counter rotation but tend to look away from it.

In experiment 2 infants aged 7 to 8 months showed a spontaneous preference for the static convex face. Together with the preference shown in experiment 1, this is consistent with a general preference for the convex stimuli and infants having seen the convex but not the hollow rotating face as convex. Critically, after habituating to the hollow face the infants here showed a novelty preference to the convex test stimulus and vice versa. This shows that the infants can discriminate between convex and concave stimuli and that habituation generalises across a 55-deg. change to a static view.

We can never know what infants actually see—ie, on what basis they make this discrimination—and logically there are any number of possibilities. For example, and as suggested by an anonymous reviewer, infants may perceive the hollow face as convex but flatter than the genuinely convex face and discriminate and respond on that basis. Such relative flattening of the illusory percept has been reported in adults viewing the illusion binocularly (Hartung et al 2005; Kroliczak et al 2006). However, the concave static stimulus used in experiment 2 and shown on the right of figure 2 does not look, at least to us as adults, like a flattened but still convex version of the genuinely convex static stimulus shown on the left of figure 2. Further, flattening would not provide an obvious explanation for why the 7- to 8-month-olds preferred the convex face in experiment 1, as both faces shown there would appear convex with the illusory flatter version counter rotating. Instead, the explanation that infants perceive the rotating hollow face as concave and not sticking out from the block appears to provide a more straightforward explanation for both the results presented here.

Perceiving a rotating concave face in an animation as concave in our study would be possible only if kinetic and perspective information is combined and rigidity assumed. Previous studies have shown that infants aged 7 months are able to combine kinetic information and perspective to disambiguate motion (Oross et al 1987) and that infants aged from 4 months show evidence for an assumption of rigidity (Kellman et al 1986). Considering these studies, one can conclude it is at least possible that the 7- to 8-month-old infants perceive the concave face as concave and rotating in synchrony with the block. In adults, the assumption of convexity and/or object specific knowledge ‘wins’ over rigidity, and an illusory convex face is seen unattached and rotating in the opposite direction. The bias of 7- to 8-month-old infants to perceive objects in general or faces in particular as convex may also not be as strong as that of adults.

We wish to note that although our results are consistent with the hypothesis that 8-month-old infants do not experience the hollow-face illusion maybe because they possess a weaker convex assumption for faces compared with adults, it cannot ever rule out the possibility that infants of this age may experience the hollow-face illusion under different circumstances. Indeed, Yonas et al (2010) have reported that 5- to 7-month-old infants attempted to reach out to the illusory ‘sticking out’ location of a nose on a hollow mask when viewing a painted three-dimensional mask monocularly. Any of the many differences in stimuli and task could explain the apparent discrepancy between the findings.

In summary, the infants tested did not show the preference for rotating concave faces shown by adults (experiment 1) and after habituation to the rotating stimuli showed a novelty preference towards static stimuli with the opposite sign of curvature (experiment 2). These results taken together suggest that infants, unlike adults, may perceive a screen-based animated rotating hollow mask as hollow.

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References

- Arterberry M E, Yonas A, 1988 “Infant sensitivity to kinetic information for three-dimensional object shape” *Perception & Psychophysics* **44** 1–6 ◀
- Fantz R L, 1963 “Pattern vision in newborn infants” *Science* **140** 296–297 doi:10.1126/science.140.3564.296 ◀
- Fantz R L, 1964 “Visual experience in infants: decreased attention to familiar patterns relative to novel ones” *Science* **146** 668–670 doi:10.1126/science.146.3644.668 ◀

- Fantz R L, Fagan J F, 1975 "Visual attention to size and number of pattern details by term and preterm infants during the first six months" *Child Development* **46** 3–18 doi:10.2307/1128828 ◀
- Granrud C E, Yonas A, Opland E A, 1985 "Infants' sensitivity to the depth cue of shading" *Perception & Psychophysics* **37** 415–419 doi:10.3758/BF03202872 ◀
- Gregory R L, 1970 *The Intelligent Eye* (London: Weidenfeld and Nicolson) ◀
- Gregory R L, 1997 "Knowledge in perception and illusion" *Philosophical Transactions of the Royal Society B: Biological Sciences* **352** 1121–1128 doi:10.1098/rstb.1997.0095 ◀
- Hartung B, Schrater P R, Bulthoff H H, Kersten D, Franz V H, 2005 "Is prior knowledge of geometry used in visually guided reaching?" *Journal of Vision* **5** 504–514 doi:10.1167/5.6.2 ◀
- Hill H, Bruce V, 1993 "Independent effects of lighting, orientation, and stereopsis on the hollow-face illusion" *Perception* **22** 887–897 doi:10.1068/p220887 ◀
- Hill H, Bruce V, 1994 "A comparison between the hollow-face and 'hollow-potato' illusions" *Perception* **23** 1335–1337 doi:10.1068/p231335 ◀
- Hill H, Johnston A, 2007 "The hollow-face illusion: object-specific knowledge, general assumptions or properties of the stimulus?" *Perception* **36** 199–223 doi:10.1068/p5523 ◀
- Imura T, Yamaguchi M K, Kanazawa S, Shirai N, Otsuka Y, Tomonaga M, Yagi A, 2008 "Infants' sensitivity to shading and line junctions" *Vision Research* **48** 1420–1426 doi:10.1016/j.visres.2008.03.011 ◀
- Johnston A, Hill H, Carman N, 1992 "Recognising faces: effects of lighting direction, inversion, and brightness reversal" *Perception* **21** 365–375 doi:10.1068/p210365 ◀
- Kellman P J, Spelke E S, Short K R, 1986 "Infant perception of object unity from translatory motion in depth and vertical translation" *Child Development* **57** 72–86 doi:10.2307/1130639 ◀
- Kleffner D A, Ramachandran V S, 1992 "On the perception of shape from shading" *Perception & Psychophysics* **52** 18–36 doi:10.3758/BF03206757 ◀
- Kroliczak G, Heard P F, Goodale M A, Gregory R L, 2006 "Dissociation of perception and action unmasked by the hollow-face illusion" *Brain Research* **1080** 9–16 doi:10.1016/j.brainres.2005.01.107 ◀
- Langer M S, Bühlhoff H H, 2001 "A prior for global convexity in local shape-from-shading" *Perception* **30** 403–410 doi:10.1068/p3178 ◀
- Oross S, Francis E, Mauk D, Fox R, 1987 "The Ames window illusion: Perception of illusory motion by human infants" *Journal of Experimental Psychology: Human Perception and Performance* **13** 609–613 doi:10.1037/0096-1523.13.4.609 ◀
- Papathomas T V, Bono L M, 2004 "Experiments with a hollow mask and a reverspective: top-down influences in the inversion effect for 3-D stimuli" *Perception* **33** 1129–1138 doi:10.1068/p5086 ◀
- Tsuruhara A, Sawada T, Kanazawa S, Yamaguchi M K, Yonas A, 2009 "Infant's ability to form a common representation of an object's shape from different pictorial depth cues: a transfer-across-cues study" *Infant Behavior and Development* **32** 468–475 doi:10.1016/j.infbeh.2009.09.002 ◀
- Tsuruhara A, Sawada T, Kanazawa S, Yamaguchi M K, Corrow S, Yonas A, 2010 "The development of the ability of infants to utilize static cues to create and access representations of object shape" *Journal of Vision* **10** 1–11 doi:10.1167/10.12.2 ◀
- Ulman S, 1979 "The interpretation of structure from motion" *Proceedings of the Royal Society B: Biological Sciences* **203** 405–426 doi:10.1098/rspb.1979.0006 ◀
- Yonas A, Cleaves W T, Pettersen L, 1978 "Development of sensitivity to pictorial depth" *Science* **200** 77–79 doi:10.1126/science.635576 ◀
- Yonas A, Corrow S, Mathison J, 2010 "When do infants use a convexity assumption to interpret a 'line drawing' and perceive spatial layout?" *Perception* 39 ECVF Abstract Supplement 109 ◀