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With or without a hole: Young infants' sensitivity for topological versus geometric property

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Abstract. Evidence from adult psychophysics, brain imaging, and honeybee's behaviour has been reported to support the notion that topological properties are the primitives of visual representation (Chen, 1982 *Science* **218** 699 – 700). Here, we ask how the sensitivity to topological property might originate during development. Specifically, we tested 1.5- to 6-month-old infants' visual sensitivity for topological versus geometric properties with the forced-choice novelty preference technique. A disk and a ring were used in the topologically different condition (experiment 1), while a disk and a triangle were used in the geometrically different condition (experiment 2). Spontaneous preferences for the disk, the ring, and the triangle were measured pairwise using the preferential looking-time technique (experiment 3). The results showed that infants could reliably discriminate stimuli based on topological differences, but failed to do so with geometric differences. Moreover, in the generalisation task, infants showed higher novelty preference for the topologically different figure (the ring). In addition, the results of both experiments cannot be attributed to a spontaneous preference for the ring or for the disk. Further analysis on individual infants' age and performance revealed two distinct developmental trends. Infants seem to be sensitive to topological differences as young as 1.5 months, while their ability to discriminate geometric differences was at chance before 3 months and gradually improved with age. Taken together, our findings suggested an early sensitivity for topological property, at least for the detection of stimuli with or without a hole.

Keywords: topological theory, infant vision, novelty preference, visual development

1 Introduction

"Is a triangle similar to a disk?" Perhaps a quick and popular answer is likely to be "no, they are different", as our common sense for shape similarity seems to be based on geometric property. However, from the point of view of topology—a branch of mathematics (Listing 1847) concerned with spatial properties that are preserved under continuous and one-to-one transformations, we might get a very different answer to the same question. Although topology is often considered one of the most abstract branches of mathematics, it can be comprehended intuitively by imagining an arbitrary distortion of clay (or something like a "rubber-sheet" distortion). The properties preserved under the transformations are called topological properties, which include the number of holes in an object, the number of objects, connectivity, and the inside – outside relationship. Thus, from the perspective of topology, a solid disk (○) and a solid triangle (△) are actually homeomorphic or topologically equivalent because a disk and a triangle can be transformed (like rubber-sheet distortion) smoothly in space without generating or destroying a hole. The topological properties of the two figures remain invariant. However, local geometric properties, such as symmetry, orientation, size, parallelism, and collinearity, may be altered by such arbitrary distortions. On the other hand, a solid disk (○) and a hollow ring (◎) may be seen as similar geometrically because they both have a shape of a circle. But from the perspective of topology they are very different, or topologically inequivalent. A ring contains a hole, but a disk contains none; the transformation from a disk to a ring has to involve creating a hole. Having a hole or not marks a salient topological difference.

Many contemporary models of visual perception follow a part-to-whole hierarchy of detecting features first and then integrating them to build objects (eg Marr 1982; Treisman 1988). A notable exception is the theory of topological perception proposed by Chen (1982). Chen's main idea is that extracting the global topological properties serves as the very starting point of object perception. The topological properties are the most robust and stable across transformations as compared with other geometrical properties, such as projective, affine, and Euclidean properties (Chen 1982, 1990; He 2008). In addition, objects of equivalent topological properties are more likely to be regarded as the same under a near-threshold condition.[1] Ever since the topological theory has been introduced, evidence from adult psychophysics (Chen 2005, for a review), brain imaging (Wang et al 2007), and even honeybee's behaviour (Chen et al 2003; see Pomerantz 2003) has been reported to support the notion that global topological properties are the very primitives of visual representation (cf Rubin and Kanwisher 1985). However, the question of how sensitivity to topological properties originates during development has not been explored. If topological properties are more "primitive", would infants be more sensitive to topological properties than to geometrical properties at a very young age?

Here we aim to explore whether 1.5- to 6-month-old infants are more sensitive to topological differences than to geometric differences. Specifically, we adopted a multiple discrete-trial familiarisation technique termed the forced-choice novelty-preference (FNP) procedure (Chien et al 2003; Civan et al 2005; see Chien et al 2010 for detail), which can be viewed as a change-detection task for infants to test infants' perceptual discriminability and generalisation. The forced-choice novelty-preference procedure is a hybrid technique that combined the familiarisation/novelty-preference paradigm (Fagan 1970) with the forced-choice preferential-looking procedure (Teller 1979). Each FNP trial contains a study and a test phase, in which two identical stimuli are presented side-by-side for several seconds (the study phase), followed by two test stimuli where one is the same as in the familiarisation and the other is a novel one (the test phase). Because young infants are known to have novelty preferences (Hunter and Ames 1988), if the differences between the familiar and the novel stimuli are discriminable to the infants, we expect that they would look consistently more at the novel stimulus than at the familiar one across trials. In addition to assessing perceptual discriminability, the FNP technique can also be used for assessing perceptual generalisation or categorisation when both test stimuli are physically different from the familiar stimulus. In this case, infants may look more at the one that appears perceptually more novel than the other.

Three experiments were conducted in the present study. In experiment 1, we adopted two topologically different but geometrically similar figures, a disk ○ (has no hole) and a ring ◎ (has a hole), to assess infants' sensitivity for topological properties such as having a hole or not. We picked this pair of stimuli because having a hole or not marked a salient topological difference, and this would be good to maximise possible differences for the infant subjects. In addition, it has been reported that curvatures seem to be a salient psychological property of a visual event for humans. Each experiment has two discrimination tasks and one generalisation task as illustrated in figure 1. Infants received the familiarised-to-disk and familiarised-to-ring discrimination

(1) The experimental paradigm focused on visual sensitivity to holes under near-threshold condition (Chen 1982, 1990). The subjects received a 5 ms tachistoscope presentation of pairs of stimuli, followed by the immediate reappearance of the pre-exposure field, and were asked to report whether the two figures in one display were the same or different (the displays were always different). The intensity of illumination of the target field was adjusted at the beginning and might be adjusted further between blocks of presentation for each subject to keep an overall probability of reporting "different" of about 50%. The performance favoured a topological-property-based explanation. The results showed that ring versus solid disk were discriminable, while solid square versus solid disk and solid triangle versus solid disk were not.

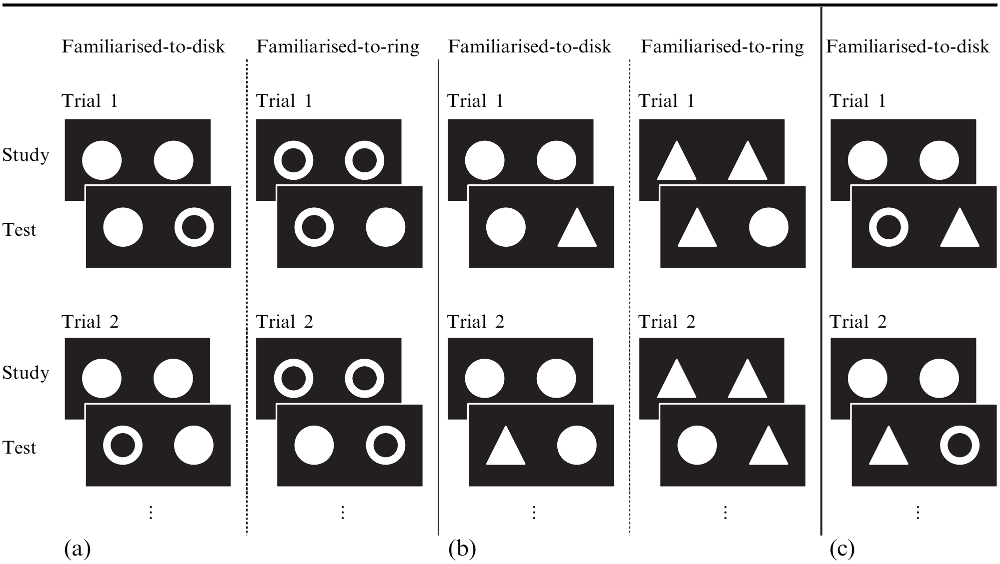


Figure 1. Illustration of the flow of (a) experiment 1 (topologically different conditions), (b) experiment 2 (the geometrically different conditions), and (c) the generalisation task in both experiments. The forced-choice novelty preference (FNP) procedure was used to test whether infants show significant novelty preference after familiarisation. Each FNP trial has two phases: a study phase and a test phase. In the study phase, two identical figures (eg two disks) appear for as long as the infant is judged to look away from the monitor display. In the test phase, based on the infant's overall looking behaviour, the observer makes a forced-choice response about the location of the novel stimulus. Because young infants are known to have novelty preferences, if the differences between the familiar and the novel stimuli are discriminable, we expect that infants would consistently look more at the novel stimulus than at the familiar stimulus. The observer is blind to the location of the novel stimulus, which is randomised across trials.

conditions (ie the familiar and the novel stimuli were reversed in these two conditions), followed by a generalisation task in which the familiarised stimulus was a pair of two identical disks and the test stimuli were a ring (topologically different) and a triangle (geometrically different).

In experiment 2, we adopted two geometrically different but topologically equivalent figures, a disk (○) and a triangle (△), to assess infants' sensitivity for geometric properties. We picked a disk and a triangle to maximise the geometric difference, as the two figures were quite different in terms of their overall shapes and local features such as curved versus straight contours, with or without corners (see Fantz and Miranda 1975; Fantz et al 1975). Infants received the familiarised-to-disk and familiarised-to-triangle discrimination conditions (ie, the familiar and the novel stimuli were also reversed in these two conditions), followed by the same generalisation task as in experiment 1. To rule out the possibility that a spontaneous preference for a particular figure may be confounded with the discriminability as well as the novelty preference in the generalisation task, we ran an additional control study. Thus in experiment 3, we used the classic visual preference technique (Fantz 1958, 1961) to test if there is any spontaneous preference for the disk, the ring, or the triangle when they were presented pairwisely.[2]

[2] The reason why we switched to looking-time measures in experiment 3 was because it is difficult to measure three different spontaneous preferences in one sample with the typical FPL method. FPL procedure is best suited for studying near-threshold stimuli condition to test whether a single stimulus, randomly appearing on the left or right side of the screen, can be detected against the background by the infant observer (Teller 1979). Because all the figures in the current study are highly visible against the background (supra-threshold), and we wish to compare them side by side, we adopted Fantz's PL method of looking-time measures.

Our predictions are as follows. If topological properties are no more primitive than geometric properties, we expect that young infants shall be able to discriminate stimuli based on both topological differences as well as geometric differences. For the generalisation task, we may find about similar preference for both the ring (topologically different) and the triangle (geometrically different). However, if topological properties are indeed more primitive than geometric ones, we expect that young infants can readily discriminate stimuli based on topological differences but not yet on geometric differences. In addition, we expect to see a higher novel preference for the topologically different stimulus, the ring, than for the geometrically different stimulus, the triangle, in the generalisation task.

2 Methods

2.1 *Experiment 1. Topologically different condition*

2.1.1 *Participants.* Fourteen healthy full-term infants ($5.6 \simeq 26$ weeks) were recruited from the Taichung Metropolitan areas by means of advertisements made through China Medical University Hospital, the university, and/or through the parenting community group on the Internet. Informed parent consent was obtained before the experiment. All infants were born within ± 21 days of their due dates and had no history of blindness or health problems reported by their parents. During each lab visit, an infant received three blocks of conditions in which the first two were discrimination tasks and the last one was a generalisation task. Thirteen infants passed the criterion of completing at least two blocks (20 trials). Eleven out of the thirteen infants completed all three blocks. One infant was tested but excluded from the final data set due to fussiness. The final sample size was thirteen with a mean age of 15.8 weeks ($SD = 6.6$ weeks).

2.1.2 *Stimuli and apparatus.* Figure 1 illustrates the flow of the FNP procedure used in experiment 1 (topologically different, the left panel) and experiment 2 (geometrically different discrimination tasks, the middle panel), and the generalisation task in both experiments (the right panel). A disk (○), a ring (◎), and a triangle (△) were adopted, and the stimulus parameters followed Wang et al (2007). The disk had a radius of 10 cm, a perimeter of 31.42 cm, and an area of 78.5 cm^2. The ring had an outer radius of 10 cm and an inner radius of 6.84 cm, yielding an outer perimeter of 31.42 cm and an area of 41.8 cm^2. The triangle had a height and a base of 10 cm, yielding a perimeter of 32.36 cm and an area of 50.0 cm^2. The distance from the central fixation and the centre of one of the stimuli was 12 cm (24 cm centre-to-centre). In the two experiments, all the stimuli were white with a mean luminance of 102 cd m^{-2} and a mean chromaticity at (0.33, 0.33) in CIE 1931 x, y coordinates. The background was always black, with a mean luminance of 1.2 cd m^{-2} and a mean chromaticity at CIE ($x = 0.33$, $y = 0.33$). Thus, each stimulus had the same high Weber's luminance contrast on the border. An Asus (AS-D360) personal computer with 22 inch LCD monitor and E-Prime (professional 2.0) software were used to run the experiment. The monitor was framed by black cardboard to match the black background of the stimuli display. The infant subject was held by a well-trained observer in front of the monitor at a distance of about 30 cm. The observer's view to the monitor was blocked, but she could see the infant's full-face view through an online video-monitor system.

2.1.3 *Procedure.* The FNP procedure (see Chien et al 2010, for detail) was used to test whether infants show significant novelty preference after familiarisation. Each FNP trial contains two phases. In the study phase, first, a central fixation cross appeared to attract the infant's attention. When the infant was judged to attend to the screen, two identical figures (eg two disks) appeared until the infant was judged to look away from the monitor display. Based on our experience, infants tend to look back and forth between the two identical stimuli in the first few trials, and the duration of the study phase usually extended about 5 – 10 s until they looked away. As the session went on, the infants' overall looking time for the stimuli pair in study phase would drop to about 2 – 4 s. In the test phase, infants were presented with two stimuli where one was the same (eg a disk) as in the familiarisation and the other was novel (eg a ring). The observer judged the infant's overall looking behaviour through the online video-monitor system and made forced-choice responses by foot pads. Within 3 – 5 s, the observer could normally obtain sufficient information (infant's first look, overall fixation) to make a novelty preference judgment. Because the current stimuli were relatively simple (cf as compared with pictures of faces or scenery), on average, the infant's looking time to either of the two test stimuli was within 1 – 3 s. Once the observer made a response, then the next trial appeared with a fixation cross. Each infant received two discrimination tasks and one generalisation task (within-subject design). The two discrimination conditions were the familiarised-to-disk and the familiarised-to-ring conditions, and the order of familiarisation type was randomised across subjects. The generalisation task was given at the end. There were 10 trials in each condition (5 repetitions of novel stimulus on the left, 5 repetitions of novel stimulus on the right), thus 30 trials in total.

2.2 *Experiment 2. Geometrically different condition*

2.2.1 *Participants.* Fourteen healthy full-term infants with similar age range ($8.6 \simeq 26.5$ weeks) were recruited from the Taichung Metropolitan areas with the same recruiting procedure and conditions as in experiment 1. An infant received three blocks of sessions in which the first two were discrimination tasks and the last one was a generalisation task. Twelve infants passed the criterion of completing at least two blocks. Eleven out of the twelve infants completed all three blocks. Two infants were tested but excluded from the final data set due to experimenter's error ($n = 1$) or fussiness ($n = 1$). The final sample size was twelve with a mean age of 16.5 weeks (SD = 5.9 weeks).

2.2.2 *Stimuli and apparatus.* The stimuli are shown in the middle (geometrically different discrimination tasks) and the right (the generalisation task) panels of figure 1. The stimulus parameters and apparatus were the same as in experiment 1.

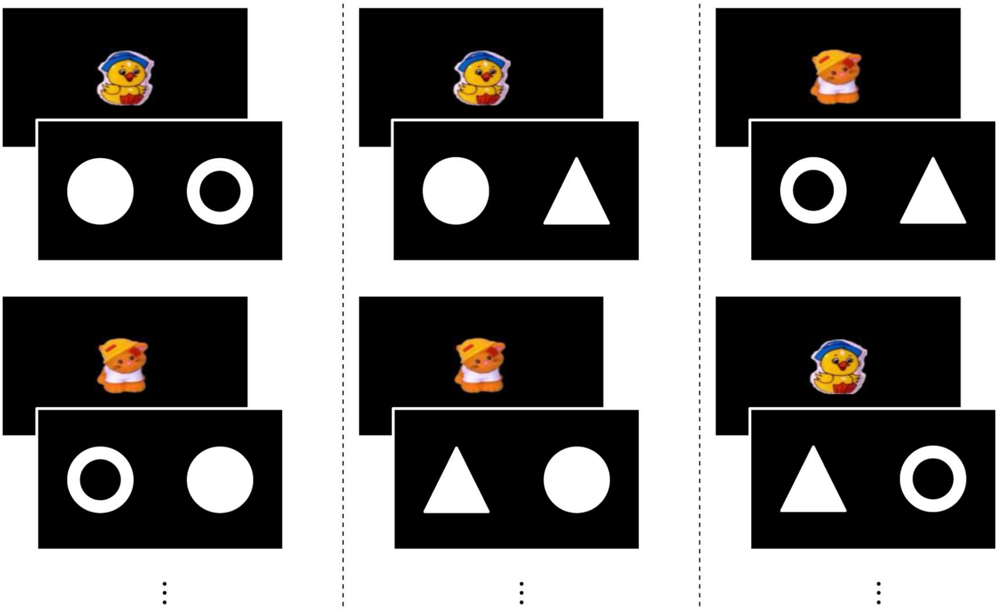
2.2.3 *Procedure.* The same FNP procedure was used in experiment 2. Again, each infant received two discrimination tasks and one generalisation task. The two discrimination conditions were the familiarised-to-disk and the familiarised-to-triangle conditions, and the order of familiarisation type was randomised across subjects. The same generalisation task was given at the end. There were a total of 30 trials.

2.3 *Experiment 3. Test for spontaneous preferences*

2.3.1 *Participants.* Fourteen healthy full-term infants within a narrower age range[3] ($11.3 \simeq 25.3$ weeks) were recruited from the Taichung Metropolitan areas with the same recruiting procedure and conditions as in experiment 1. All infants were born within ±21 days of their due dates and had no history of blindness or health problems reported by their parents. An infant received one block of condition with a total of 6 trials presented in a random order. All fourteen infants passed the criterion of completing at least 4 trials. The final sample was divided into two groups with a mean age of 18.29 weeks ($n = 7$, SD = 3.5 weeks) for the younger group and a mean age of 22.8 weeks ($n = 7$, SD = 1.7 weeks) for the older group.

(3) It would be ideal if the age range in experiment 3 could match exactly those in experiments 1 and 2. Experiment 3 was an addition suggested by one reviewer during the peer-review process. Given that we had limited time to complete the data collection, and we could not get enough younger infants during that time frame. However, the discrepancy in the age range should not be a serious issue, because the age range in experiment 3 can be seen as a subset that falls within the age ranges of both experiments 1 and 2.

2.3.2 *Stimuli and apparatus.* The stimuli are shown in figure 2. Basically, all three test pairs—a disk (◯) versus a ring (◎), a disk (◯) versus a triangle (△), and a ring (◎) versus a triangle (△) were used. The stimulus parameters (ie size, luminance, and Weber's contrast) and the apparatus were the same as in experiments 1 and 2. E-Prime (professional 2.0) software was used to run the experimental program. The monitor was framed by black cardboard to match the black background of the stimuli display. A hidden webcam beneath the monitor recorded infants' looking behaviour during the whole experimental session. The infant subject was held by his/her mother (or father) in sitting position at a distance of about 30 cm from the monitor display. The holder's view to the monitor was blocked and was instructed not to pay attention to the display.



(a) (b) (c)

Figure 2. [In colour online, see http://dx.doi.org/10.1068/p7031] Illustration of the stimuli and procedure of experiment 3 (test for spontaneous preferences). Three test pairs, (a) a disk (◯) versus a ring (◎), (b) a disk (◯) versus a triangle (△), and (c) a ring (◎) versus a triangle (△), were tested for spontaneous preference without any prior familiarisation. In each trial, an animated, attractive cartoon figure appeared in the centre of the screen to attract the infant's attention to the monitor display. When infants were judged to be attentive, a pair of test stimuli appeared on the display for 20 s. Infants' looking time for either stimulus during the 20 s period was recorded and scored. Each infant received a total of six trials shown in a random order. In this experiment, the traditional looking-time technique was employed, and the percentage of the looking time spent on one of the stimuli over the total time was calculated as the preference score, in which 50% indicates no preference.

2.3.3 *Procedure.* We adopted the classic preferential looking technique (Fantz 1958, 1961) in which an infant's looking time spent on either stimulus of the test pair was recorded. In each trial (see figure 2), an animated, attractive cartoon figure appeared in the centre of the screen to attract the infant to the monitor display. When infants were judged to be attentive, a pair of test stimuli appeared on the display for 20 s. An infant's looking time for either stimulus during the 20 s period was recorded. Each infant received a total of 6 trials presented in random order. An infant's looking time was scored by two blind observers trial by trial; the percentage of the looking time spent on one stimulus over the total looking time was calculated as the preference score, in which 50% indicates no preference. Pearson's correlations (r) for the right and the left side of the test stimuli across trials were taken as the interobserver reliability. The reliability between the two observers was fairly high; the mean correlations reached 0.93 for the right side and 0.92 for the left side averaged over the fourteen subjects.

3 Results

The dependent variables in both experiments 1 and 2 were the "observer's percent correct" for the discrimination tasks (ie there was always a correct answer because the stimulus in the test phase was physically novel) and "preference score" for the generalisation task (ie there was no correct answer because both test stimuli were novel). By definition, the OPC score was computed as the percentage of the trials in which the observer correctly judged the locations of the novel stimuli in the test phase (ie the one that did not appear in the study phase by definition) based on the infant's looking behaviours. If the infant can discriminate both topological and geometric differences, we expect to obtain greater-than-chance OPCs (significant novelty preferences) for both experiment 1 (topologically different) and experiment 2 (geometrically different). However, if topological properties are more primitive than the geometric ones, we expect to see a greater-than-chance OPC only in experiment 1 and not in experiment 2. Unlike the generalisation task of experiments 1 and 2, the dependent variable in experiment 3 was a slightly different kind of preference score; it was calculated on the basis of the percentage of the looking time spent on one of the test stimuli over the total looking time for two stimuli in a trial-by-trial fashion. Note that the FNP method was employed in experiments 1 and 2, while a rather different looking-time procedure was used in experiment 3. Although both methods can effectively inform us whether there is a significant novelty preference or spontaneous preference for a particular pattern, owing to the very different nature of the two measurements, it is not proper to directly compute statistical comparisons or compare the magnitude of preference between the results obtained in experiment 3 and the results obtained in experiments 1 and 2.

3.1 *Results of experiment 1*

Table 1 illustrates the group performance for all the stimulus conditions in experiments 1 and 2. In experiment 1 (the topologically different discrimination tasks) 1.5- to 6-month-old infants reliably looked more at the novel stimulus in the test phase (mean OPC score = 60.5%, $t_{12} = 4.41$, $p < 0.001$), no matter which one was the familiarised stimulus (familiarised-to-disk, mean OPC score = 61.7%, $t_{12} = 2.54$, $p = 0.14$; familiarised-to-ring, mean OPC score = 58.5%, $t_{12} = 1.86$, $p = 0.045$), indicating a successful discrimination between the two topologically different figures. If we split the group of infants into two halves by age, the mean OPC scores across the two familiarisation conditions for the younger infants ($n = 7$, mean age = 11.0 weeks) and for the older infants ($n = 6$, mean age = 21.4 weeks) were both significantly greater than chance (younger group: 60.7%, $t_6 = 3.58$, $p = 0.008$; older group: 59.4%, $t_5 = 2.27$, $p = 0.036$). In terms of individual's data, eleven out of the thirteen infants' OPC scores were above the chance level, showing that indeed the majority of the infants could reliably discriminate between a disk and a ring. For the generalisation task, being familiarised with disks, the infants looked more at the "ring" pattern (mean preference score = 71.8%, $t_{12} = 6.70$, $p < 0.001$) in the test phase, suggesting that the ring appeared to be perceptually more "different" to the infants than the triangle even though both figures were physically novel. For split-age analysis, mean novelty preference scores for the younger and the older groups were both significantly greater than chance (younger group: 71.7%, $t_6 = 3.60$, $p = 0.008$; older group: 72.0%, $t_5 = 11.00$, $p < 0.001$), and the difference between them was not significant ($p = 0.486$). In other words, infants across this age range could better detect a change in topological difference

Table 1. The group performance during the test phases. Upper rows: mean observer's percent correct (OPC) scores for the topologically different (experiment 1) and the geometrically different (experiment 2) discrimination tasks. Bottom rows: mean preference scores for the generalisation tasks.

Discrimination tasks	Observer's percent correct score[a]/%			
	M	SE	t^{b}	*p*
Experiment 1: topologically different conditions				
familiarised-to-disk	61.7	4.6	2.54	0.014
familiarised-to-ring	58.5	4.6	1.86	0.045
combined	60.5	2.4	4.41	0.001
Experiment 2: geometrically different conditions				
familiarised-to-disk	46.5	3.0	−1.15	0.136
familiarised-to-triangle	55.4	3.8	1.44	0.089
combined	51.7	2.7	0.64	0.267
Generalisation tasks	**Preference score[c]/%**			
	M	SE	t^{b}	*p*
Experiment 1: generalisation (familiarised-to-disk)				
preference for the ring	71.8	3.3	6.70	0.000
preference for the triangle	28.2	3.3	−6.70	N/A
Experiment 2: generalisation (familiarised-to-disk)				
preference for the ring	67.7	4.9	3.59	0.002
preference for the triangle	32.3	4.9	−3.59	N/A

[a] The OPC score is the dependent variable in the discrimination tasks. It is computed as the percentage of the trials in which the observer, based on the infant's overall looking behaviour, correctly judged the locations of the novel stimuli in the test phase. [b] The *t* statistic is computed as $(M - 0.5)\ \mathrm{SE}^{-1}$, one-tailed test. [c] The preference score is the dependent variable in the generalisation task. The two stimuli in the test phase are both novel as compared to the familiarised disk. N/A is not applicable.

(disk → ring) than a change in geometric difference (disk → triangle) when the two were paired together; this is consistent with the positive results of the topologically different discrimination conditions.

3.2 *Results of experiment 2*

In experiment 2 (the geometrically different discrimination tasks), however, infants did not look significantly more at the novel stimulus in the test phase (mean OPC score = 51.7%, $t_{12} = 0.64$, $p = 0.267$), indicating that the two geometrically different figures seemed to be not discriminable for this age range as a whole. However, if we split the group of infants into two halves by age, we found that actually the mean OPC score of the older infants ($n = 6$, mean age = 21.3 weeks) was significantly greater than chance (55.7%, $t_5 = 3.88$, $p = 0.006$), whereas the mean OPC score of the younger infants ($n = 6$, mean age = 12.6 weeks) was still at chance (46.1%, $t_5 = -1.46$, $p = 0.102$). In addition, the difference between the two group means was statistically significant ($p = 0.009$), indicating a meaningful age difference in the discrimination performance. In terms of the individual's data, six out of the twelve infants' OPC scores were below or equal to the chance level; of the six infants who could not discriminate between the disk and the triangle, five infants belonged to the younger group. For the generalisation task, being familiarised with disks, the infants reliability looked more at the "ring" pattern (mean preference score = 67.7%, $t_{11} = 3.59$, $p = 0.002$) in the test phase, suggesting that the ring also appeared to be perceptually more "different" to the infants than the triangle when both figures were physically novel. For split-age analysis, the younger group mean novelty preference for the ring was marginally significant (younger group: 62.5%, $t_5 = 1.62$, $p = 0.083$), while the mean preference for the ring of the older group was significantly greater than chance (older group: 74.0%, $t_5 = 4.71$, $p = 0.003$). However, the difference between the two groups did not reach statistical significance ($p = 0.162$). Again, this pattern of results indicated that infants could better detect a change in topological difference (disk → ring) than a change in geometric difference (disk → triangle) when the two were paired together; this is consistent with the null results of the geometrically different discrimination conditions.

3.3 *Further analyses combining experiments 1 and 2*

The results of the discrimination tasks were further supported by a two-way mixed ANOVA combining experiments 1 and 2 (between-subjects factor: experimental condition; within-subjects factor: familiarisation type). There was a main effect of the experimental condition ($F_{1,23} = 11.275$, $p = 0.003$, $\eta_p^2 = 0.329$) showing the mean OPC score for the topologically different discrimination tasks (experiment 1) were significantly greater than that for the geometrically different discrimination tasks (experiment 2). The main effect of familiarisation type was not significant ($F_{1,23} = 1.152$, $p = 0.294$, $\eta_p^2 = 0.048$), meaning that the obtained OPC scores did not differ because of the types of familiarised stimuli. Moreover, the interaction between experimental condition and familiarisation type was not significant either ($F_{1,23} = 1.887$, $p = 0.183$, $\eta_p^2 = 0.076$).

Figure 3 illustrates a further analysis on age versus individual infant's OPC score for experiments 1 and 2. Two distinct developmental trends can be observed. For experiment 1 (marked in solid squares), infants were able to discriminate topological differences (their OPC scores were above chance) as young as 6 weeks and maintain the performance level across age. For experiment 2 (marked in open triangles), infants' ability to discriminate geometrical differences was about chance level before 14 weeks, and gradually improved between 8 and 28 weeks. Correlation analysis further supported this notion. For the topologically different condition the Pearson's r between infant's OPC and age was not significant from zero ($r = -0.23$, $p = 0.224$), whereas in the geometrically different condition the Pearson's r was significantly greater than zero ($r = 0.59$, $p = 0.025$), indicating a positive correlation between the OPC score and age. This pattern of results

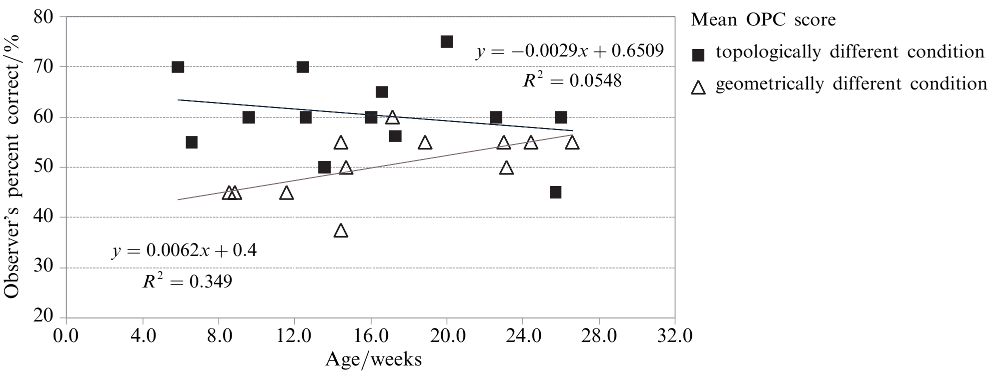


Figure 3. The scatter plots for individual infant's age versus their performance in the two discrimination tasks. The abscissa represents an infant's age in weeks. The ordinate depicts the observer's percent correct (OPC) scores for the discrimination tasks. Two distinct developmental trends can be observed. For experiment 1 (the topologically different conditions, marked in solid squares), infants seem to be readily sensitive to topological differences (the OPC scores were above chance) as young as 6 weeks and maintain the performance across age. For experiment 2 (the geometrically different conditions, marked in open triangles), their ability to discriminate geometrical differences is at chance before 14 weeks and gradually improves between 8 and 28 weeks. This pattern of results suggests that the ability to process topological properties seems to be present and functioning very early in life, while the ability to process geometric properties may develop later.

suggests that the ability to process topological properties seems to be present and functioning early in life, while the ability to process geometric properties may come later and gradually improve with age and maturation.

3.4 *Results of experiment 3*

Table 2 illustrates the mean spontaneous preference scores for the younger and the older infants. For a pair of a disk versus a ring, the younger group looked longer at the ring (62.4%) than the disk (36.7%), and the preference reached significance ($t_6 = 3.80$, $p = 0.009$). However, the older group did not show a significant preference for either the ring (52.7%) or the disk (47.3%). For the pair of a disk versus a triangle, the younger group did not show a significant preference for either the disk (53.4%) or the triangle (46.6%). Interestingly, the older group looked longer at the disk (66.0%) than the triangle (34.0%), and the preference was significant ($t_6 = 2.76$, $p = 0.033$). For the pair of a ring versus a triangle, the younger group looked slightly longer at the ring (57.4%) than the disk (42.6%), but looking preference did not reach statistical significance. Similarly, the older group looked slightly longer at the ring (59.8%) than the disk (40.2%), but the preference was not statistically significant either. To sum up, the tests of spontaneous preferences for the three pairs showed the following pattern. First, for the topologically different stimuli, such as the ring paired with the disk or with the triangle, the only statistically significant preference for the ring was found in the pair of a disk versus a ring and only for the younger infants. Second, for the geometrically different stimuli, such as a disk versus a triangle, a preference for the disk was only present in the older group. Third, caution must be taken when one

Table 2. The results of the spontaneous preference tests (experiment 3). Upper rows: mean preference scores for the younger group. Bottom rows: mean preference scores for the older group.

Younger group ($n = 7$) (mean age = 18.3 weeks)	Preference score[a]/%			
	M	SE	t[b]	*p*
Pair 1: Ring versus disk				
preference for the ring	62.4	3.3	3.80	0.009
preference for the disk	36.7	3.3	−3.80	N/A
Pair 2: Disk versus triangle				
preference for the disk	53.4	5.7	0.59	0.572
preference for the triangle	46.6	5.7	−0.59	N/A
Pair 3: Ring versus triangle				
preference for the ring	57.4	6.1	1.21	0.271
preference for the triangle	42.6	6.1	−1.21	N/A
Older group ($n = 7$) (mean age = 22.8 weeks)	**Preference score[a]/%**			
	M	SE	t[b]	*p*
Pair 1: Ring versus disk				
preference for the ring	52.7	4.5	0.59	0.571
preference for the disk	47.3	4.5	−0.59	N/A
Pair 2: Disk versus triangle				
preference for the disk	66.0	5.8	2.76	0.033
preference for the triangle	34.0	5.8	−2.76	N/A
Pair 3: Ring versus triangle				
preference for the ring	59.8	7.5	1.29	0.242
preference for the triangle	40.2	7.5	−1.29	N/A

[a] The preference score is the dependent variable, which is computed as the proportion of the looking time spent on one stimulus over the total looking time in a particular trial. [b] The t statistic is computed as $(M - 0.5)\ \mathrm{SE}^{-1}$, two-tailed test. N/A is not applicable.

interprets spontaneous preference data. In particular, a presence of spontaneous preference for a given test pair indicates discriminability between the two stimuli but not vice versa. In other words, an absence of spontaneous preference does not imply a lack of discriminability; it could simply be that the two stimuli were distinguishable and equally interesting to the infant.

4 Discussion

Through the use of the multiple-discrete-trial FNP technique, the present study found that, on average, 1.5- to 6-month-old infants could reliably discriminate topologically different figures (a disk and a ring) but not topologically equivalent ones (a disk and a triangle). Although a disk and a ring share a very similar geometric shape of a circle, the majority of the infants of this age range could reliably distinguish between the two. On the other hand, a disk and a triangle differ in their overall geometric shapes as well as a few local features (eg straight versus curved edge); however, the younger infants (not the older infants) failed to discriminate these differences as if the two shapes were indistinguishable metamers. These results hold for the group means as well as the individual's data. In addition, even though there is a slight spontaneous preference for the ring in the younger infants in experiment 3, the results of experiment 1 cannot be explained by the mere effect of spontaneous preference for the ring, because fairly equal OPC scores were obtained in both the familiarised-to-disk (ie the ring is the novel pattern) and the familiarised-to-ring (ie the disk is the novel pattern) conditions. Furthermore, the presence of a spontaneous preference (ie implies discrimination) for the disk over the triangle in older infants also supports the split-age analysis that only older infants succeeded in the geometrically different discrimination task.

In the generalisation task when the two test stimuli were physically novel, infants reliably looked more at the topologically different figure (the ring) than the geometrically different figure (the triangle) in both experiments 1 and 2, suggesting that the "ring" appeared to be perceptually more "different" to the infants than did the triangle. In other words, the triangle and disk were seen as more similar to each other. In addition, even though in experiment 3 there was a slight tendency to look a little longer at the ring when paired with the triangle, the preference was not statistically significant for both age groups. Moreover, the correlation analysis on individual infant's performance versus age revealed two distinct developmental trends. Infants seem to be readily sensitive to topological differences as young as 6 weeks old, while their ability to discriminate geometrical differences (topologically equivalent) improves between 8 and 28 weeks.

Could there be other non-topological factors that might explain the current results? We know that young infants' photoreceptors are very immature at birth, and their visual sensitivity is rather poor (Abramov et al 1982; Yuodelis and Hendrickson 1986); infants' photopic spectral sensitivity, visual acuity, and contrast sensitivity improve substantially in the first year of life (Atkinson and Braddick 1989; Banks and Shannon 1993; Peeples and Teller 1978; Teller 1997). Given that young infants have limited spectral sensitivity, it could be argued that infants may just attend to whichever stimulus gives the strongest signal. In our case, all stimuli were above luminance threshold and had the same high Weber's contrast on the edge as well as the same length of perimeter but differed in area size. Among the three figures, the disk (78.5 cm^2) was largest, followed by the triangle (50.0 cm^2) and the ring (41.8 cm^2). It is true that the largest stimulus may yield the highest total luminance flux, but whether this is the basis for infants' response is another story. If infants will always respond to the one that gives the strongest signal, we expect that infants shall always prefer the disk in all four discrimination conditions, and the triangle in the generalisation condition when paired with the ring.

However, this did not happen. Our infants clearly preferred the ring (had the smallest area size) in the familiarised-to-disk condition and in the generalisation task. Another possibility is that the infants could discriminate the topologically different figures but not the geometrically different figures because the former had a larger difference in size (or in delta luminance flux) than the latter. This is also unlikely because the size difference between the disk – ring pair (36.7 cm^2) and the disk – triangle pair (28.5 cm^2) was not that big at all, but the behavioural consequences differ drastically. In addition, if it is due to area-size difference, we shall expect to get a much smaller preference score in the generalisation condition when the ring was paired with the triangle in which the difference was only 8.2 cm^2. However, this did not happen either. In fact the opposite result was obtained when the preference score was slightly higher (71.0% in experiment 1 and 63.8% in experiment 2) than that in the discrimination condition (60.5%) (see table 1).

In addition to the above argument, with a different experimental design we are currently running a large new set of stimulus pairs with the intent to control for the amount of white area as well as to explore some different topological properties, such as numbers of holes (ie one hole versus two holes). Among these sets of stimuli, there are two particularly interesting pairs: (i) S-shape versus ring, and (ii) the ring with a small hole versus the ring with a large hole. The former pair of figures have identical white area and perimeter, but are topologically different (ie the S-shape has no hole while the ring has a hole). On the contrary, the latter pair have the same outer contours shape but differ in the white area, and they are also topologically equivalent (ie they both have only one hole). Our small pilot results ($N = 9$) showed that 4 – 5-month-old infants exhibited a (marginally) significant discrimination between the topologically different S-shape and a ring (mean OPC $= 0.65$, $t_8 = 2.86$, $p = 0.052$), suggesting that the discrimination was not governed by the difference in the white area. Moreover, our pilot data ($N = 9$) showed no successful discrimination between the ring with a large hole and the ring with a small hole (mean OPC $= 0.43$, $t_8 = -0.78$, $p = 0.47$). This is also interesting! Because it suggests that when the topological properties are equivalent, young infants cannot tell them apart when the two figures differ in the white area.

How do our findings fit with the existing literature on pattern perception in early infancy? At first glance, our result that younger infants failed to discriminate between a disk and a triangle seems to challenge the early report by Fantz and Miranda (1975) showing that neonates have a measurable visual preference for curved over straight contour, as long as the borders were not enclosed. In fact, we really do not consider our results inconsistent with Fantz and Miranda's (1975) for several reasons. First of all, the original stimuli used in Fantz and Miranda (1975) were spatially complex patterns such as bull's-eye, stripes, and curved- versus straight-contoured concentric patterns. The preferential-looking results of Fantz and Miranda (1975) showed an overall preference for curvature for their Form Type I, II, and III, but not for Type IV (which were the pair of bull's eye versus horizontal stripes). In addition, when the patterns were enclosed with the same square contour, the preference for curvature completely disappeared for all pairs of forms. Second, the stimuli in our study were a homogenous disk and a homogenous triangle, which were quite different from the spatially complex patterns used in Fantz and Miranda (1975). Third, in our experiment 3, we found a significant spontaneous preference for a disk when paired with a triangle in the older infants, which may be taken as evidence of curvature preference. However, our findings seem to challenge a well-cited study by Slater et al (1983) using the habituation method which found newborns were able to discriminate simple geometric shapes. In their study, monocular viewing conditions were used: newborns were habituated with one eye as the "seeing" eye, and posthabituation novelty preferences investigated with the other eye. Significant preferences were found both for a novel colour (experiment 1) and for a novel shape (experiment 2), including crosses, circles, and triangles. However, to our best knowledge, this newborn study has not been replicated since publication. Further experiments directly testing newborns with similar stimulus conditions may be needed.

Nevertheless, our finding is in agreement with a recent study on newborn's perceptual categorisation. Through the use of familiarisation and the visual-paired-comparison technique, Turati et al (2003) showed that neonates can categorise the so-called "closed" and "open" geometric forms. In fact, from the point of view of topology, all the exemplars within the same category (either the "closed" or the "open" form) were topologically equivalent. It can be argued that the closure – openness can be perceived as a primitive global topological (Chen 1982, 1990) or configural – wholistic (Kimchi and Bloch 1998) property that can be extracted very early on by the visual system as a primitive representation. In addition, our finding that young infants are readily sensitive to a global topological property than to a local geometric property seems to be consistent with the Frick et al (2000) study. They investigated the temporal processing sequence of local and global visual properties with 3-month-old infants. Across the experiments, a global pattern was discriminated under conditions of less familiarisation than was necessary for local elements to be discriminated, thus indicating a global precedence in the sequence of visual processing at 3 months of age. Furthermore, on a grand scale, our viewpoint that young infants are more sensitive to the global topological property is also consistent with the differentiation view of the ecological perception approach (Gibson 1969). In this perspective, perceptual development and perceptual learning are seen as a differentiation process, in which maturation and experience leads to extraction of finer detail.

In summary, the present study had three major findings. First, we found that the ability to detect global topological properties, at least for the patterns with or without a hole, seems to be present and functioning very early in life. Second, the ability to process local geometric properties, at least for curved versus straight edges may be less mature and gradually improves in the first 6 months of life. Third, the early discriminability for topologically different patterns, such as a ring versus a disk, cannot be attributed to a spontaneous preference for the ring. This pattern of results is consistent with the idea that global topological properties are more primitive than local geometric properties, and thus the sensitivity to the former is present earlier in life. Clearly, the repertoire of topological properties is more than having a hole or not. Further investigation is needed to include more stimulus manipulations for other types of topological differences that are controlled for low-level factors, such as luminance, size, perimeter, and spatial frequency. In conclusion, the present study may be the first attempt to explore whether topological properties are more primitive than geometric properties with the developmental approach and the answer we found was affirmative.

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