

Late Development of Early Visual Perception: No Topology-Priority in Peripheral Vision Until Age 10

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Topological property (TP) is a basic geometric attribute of objects, which is preserved over continuous and one-to-one transformations and considered to be processed in early vision. This study investigated the global TP perception of 773 children aged 6–14, as compared to 179 adults. The results revealed that adults and children aged 10 or over show a TP priority trend in both central and peripheral vision, that is, less time is required to discriminate TP differences than non-TP differences. Children aged 6–8 show a TP priority trend for central stimuli, but not in their peripheral vision. The TP priority effect in peripheral vision does not emerge until age ~10 years, and the development of central and peripheral vision seems to be different.

A wealth of research on visual development has emerged since the last decades of the 20th century. The majority of these studies focused on infants' visual development as the first year of life is commonly considered a critical period of visual development (Braddick & Atkinson, 2011). In contrast, significantly less attention has been focused on the visual development of older children (Leat, Yadav, & Irving, 2009). Different visual functions mature at different ages, however, and children's visual function is also gradually discovered to be not fully developed (Bremner & de Fockert, 2016; Ellemberg et al., 2004; Leat et al., 2009; Lewis & Maurer, 2005; Nardini, Bedford, & Mareschal, 2010; Newcombe, 2019). For example, the perception of global structure in an array of line segments matures between the ages of 6–9 years (Lewis et al., 2004). A recent study revealed that perceptual and cortical fusion of depth cues does not emerge in the visual cortex until age ~11 years (Dekker et al., 2015). The evidence shows that although most visual functions appear during infancy, some of them could be developing and some could even not emerge until late childhood. On the other hand, studies have shown that children's basic visual functions are similar to adults', although have not fully matured. For example, the spatial contrast sensitivity among 4-year-old children follows a curve similar to that of adults, before reaching the adult level at 6–7 years (Ellemberg, Lewis, Chang, & Maurer, 1999).

This study demonstrates that the peripheral vision of children aged 6–8 years functions differently than for adults when discriminating geometric properties of objects, that is, topological property (TP) and non-TP shapes. Topology, which is a branch of mathematics, describes the basic spatial characteristics of shapes that are preserved across continuous smooth shape transformations, such as twisting, bending, and stretching. The TP of an object is a geometric property that is preserved over these continuous and smooth "rubber-sheet" transformations. The number of holes in a figure is an example TP. For example a bun (no holes) is topologically different from a doughnut (a hole).

Topological perception has been suggested to be crucial for the perceptual stability of variable visual input (He, 2008). The human visual system has been shown to be highly sensitive to topological differences in images (Chen, 1982). Even 0- to 4-day-old human neonates possess the ability to distinguish TP differences, while they are unable to identify differences in nontopological geometric properties (non-TP; Lin, Hui-Lin Chien, & Hu, 2016). For instance, neonates are able to differentiate a solid disk and a hollow ring, but not for a solid disk and a solid triangle. Substantial evidence from decades of research (Chen, Zhang, & Srinivasan, 2003; Han, Humphreys, & Chen, 1999; He, Zhou, Zhou, He, & Chen, 2015; Huang, Zhou, & Chen, 2011; Huang et al., 2018; Meng et al., 2018, 2019; Pomerantz, 2003; Zhou, Luo, Zhou, Zhuo, & Chen, 2010; Zhuo et al., 2003) supports the TP priority hypothesis, which posits that the TP is processed prior to non-TP attributes of a visual stimulus (Chen, 2005). Wu and her colleagues conducted a series of behavioral and functional MRI experiments showing that, compared to central vision, peripheral vision is more engaged in the rapid detection of topological differences (Wu, Wang, Zhuo, & Chen, 2017). Evidence shows that the speed of visual information processing increases with eccentricity (Carrasco, McElree, Denisova, & Giordano, 2003). Since peripheral vision shows different processing characteristics from central vision, there could be differences in the development of central and peripheral vision. This study aimed to investigate how the TP priority trend develops in children in their central and peripheral visual field.

We recruited 773 children aged 6–14 years and 179 adults, to explore the development of topological and nontopological geometric perception in central and peripheral vision. In Experiment 1, we used two types of figures, that is letter-like figures and arrow-triangle figures, to explore the performance of children from 6 to 14 years old and adults on topological and nontopological discrimination in the central and peripheral visual fields. The purpose of using large samples in Experiment 1 was to

confirm the finding from a preliminary experiment that 6-year-old children may have different topological perception than adults. According to previous research findings, the physical size of a stimulus affects the processing speed (Carrasco et al., 2003). In Experiment 2 we tested the possible effect of stimulus size on performance. And in Experiment 3, we examined the influence of task difficulty on TP priority effect. Relatively small samples were adopted in Experiments 2 and 3 to explore the effects of some possible confounding factors.

Method

Ethics statement

Experiments were conducted in accordance with the tenets of the World Medical Association Declaration of Helsinki, and the study was approved by the Human Research Ethics Committee of our institute. All participants and the guardians of participating minors provided informed written consent before participation in the study.

Participants

We recruited a total of 952 Chinese participants from the affiliated school of our institute and local communities between November 2018 and January 2020. Children were all recruited from the school, and this research was one of our cooperative projects with the school. Adult participants were recruited from local communities, mainly graduate students. There were 620 and 286 participants in Experiment 1a and 1b, respectively (see Table 1 for details). It should be noted that the original sample size of Experiment 1b was 198 and then we increased sample size post hoc after initial review, in order to make the sample size more closely comparable with Experiment 1a and to detect the effect sizes observed in Experiment 1a. Eighteen participants took part in Experiment 2, 5 male, M (SD) age = 24.4 (1.5) year; and 28 participants in Experiment 3, 12 male, M (SD) age = 25.0 (2.6) year. All

participants reported normal or corrected-to-normal visual acuity. All were right-handed and naive to the purpose of the study.

Stimuli

Stimuli were presented on an LCD monitor (60-Hz refresh rate) that was viewed from a distance of 57 cm in a dimly lit room. Stimuli (25 cd/m^2) were presented in pairs, one stimulus on each side of the central fixation point. The background luminance of the screen was 20 cd/m^2 . Other possible confounding factors such as luminance, overall size, stroke width, the number of lines and spatial frequency were controlled for stimuli in this study.

In Experiment 1, as shown in Figure 1A, four letter-like figures (“ε”, “Ϝ”, “ρ”, and “ϛ”) and arrow-triangle geometrical figures (e.g., “Δ”, “∇”) were adopted in Experiment 1a and Experiment 1b, respectively. In Experiment 1a, the letter stimuli can be divided into two types according to TP difference in the number of holes, that is, “ε” and “Ϝ” belong to the “no-hole” group, and are topologically different from the “hole” group to which “ρ” and “ϛ” belong. The figures in each of the two groups, for example, “ε” and “Ϝ” have the same TP but different shapes, which means that figures within one group are non-TP different. The figures in Experiment 1b can also be divided into “hole” (e.g., “Δ”) and “no-hole” (e.g., “∇”) group. We measured the ability to discriminate both TP and non-TP differences. To measure discrimination abilities for central and peripheral vision, the stimuli were presented at an eccentricity of 2° (central) or 12° (peripheral). Central stimulus was $1^\circ \times 1.75^\circ$ in Experiment 1a and $1^\circ \times 1^\circ$ in Experiment 1b, and peripheral stimulus was magnified to $3^\circ \times 5.25^\circ$ in Experiment 1a and $3^\circ \times 3^\circ$ in Experiment 1b, according to the cortical characteristics in the peripheral visual field (Rovamo & Virsu, 1979). The stroke width of peripheral stimuli was scaled with magnification.

To exclude the possible effect of stimulus size on performance, the same-size letter stimuli ($2^\circ \times 3.5^\circ$) were tested in the central and peripheral visual fields

Table 1
The Number of Participants for Each Age Group in Experiment 1a and 1b

	Age group	6	8	10	12	14	Adults
Experiment 1a	N (male)	141 (70)	104 (59)	49 (22)	138 (78)	94 (51)	94 (38)
	Age, M (SD)	6.1 (0.3)	8.9 (0.4)	10.1 (0.3)	12.1 (0.2)	14.5 (0.3)	26.9 (5.7)
Experiment 1b	N (male)	60 (28)	67 (33)	47 (25)	42 (22)	31 (19)	39 (20)
	Age, M (SD)	6.6 (0.5)	8.7 (0.5)	10.2 (0.6)	12.3 (0.5)	13.3 (0.5)	23.9 (1.3)

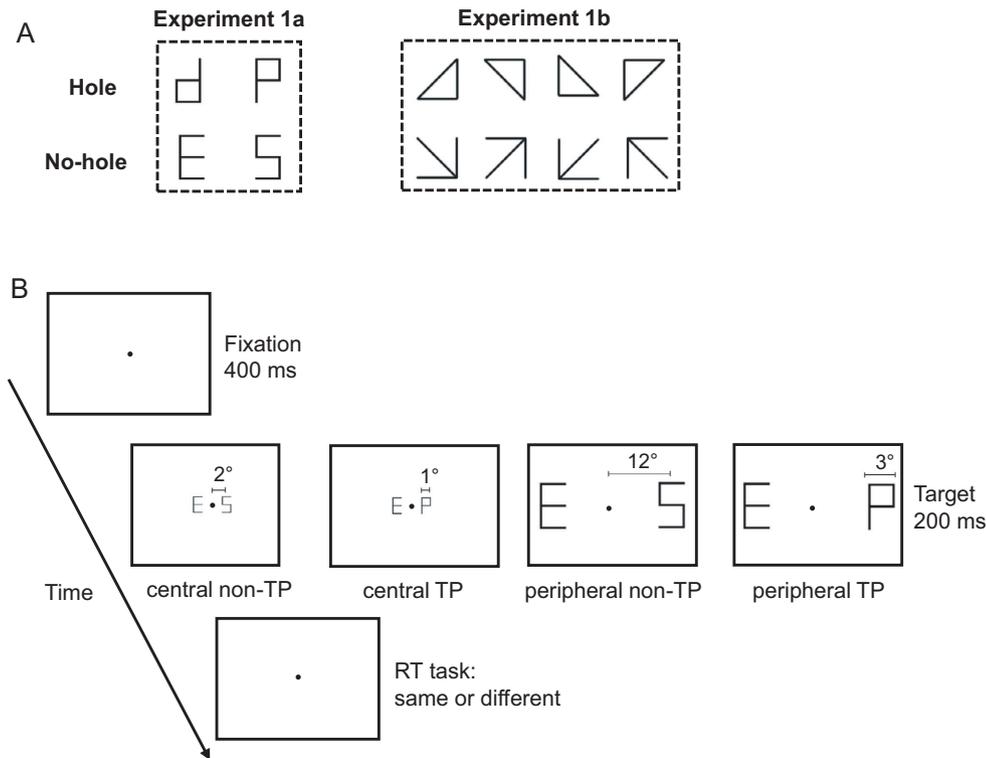


Figure 1. Example stimuli and experimental procedure. (A) Overview of the experimental procedure and examples of the four types of stimulus combinations (central non-TP, central TP, peripheral non-TP, and peripheral TP). (B) The letter-like figures (“E,” “S,” “P,” and “d”) and the arrow-triangle figures (e.g., “△” “↗”) used as stimuli during Experiment 1a and Experiment 1b, respectively. The stimuli figures in each experiment were matched in area, luminance, overall size, stroke width, the number of lines, and spatial frequency. “P” and “d” (or “E” and “S”) have the same TP (hole) but different shapes and are, therefore, non-TP different. “E” and “S” have different number of holes, thus they are TP different. RT = reaction time; TP = topological property.

in Experiment 2, otherwise, the stimuli were identical to Experiment 1a. The stimuli in Experiment 3 were the same as those used in Experiment 1.

Procedure

In Experiment 1, as shown in Figure 1B, in each trial two figures were shown on the right and left of the fixation point for 200 ms at an eccentricity of either 2° (central) or 12° (peripheral). The short duration of targets was set to ensure that no saccades occur during the presentation of target stimuli (Fuchs, 1967; Purves et al., 2001). Participants had to maintain fixation at a central point and make a speeded response to whether the two stimuli were the same or not by pressing one of the two specified keys on the keyboard (identical in 50% of the trials). Participants were required to respond accurately and fast, but there was no time limit. Reaction Times (RTs), that is, time taken from the end of stimuli presentation to received response from participants, were measured for each trial. In

total, there were four types of combinations, that is, two eccentricities (central and peripheral) and two discrimination types (TP and non-TP). Each of the four combination types (TP or Non-TP Discrimination × Central or Peripheral) was arranged in a separate block, with the block order balanced between participants. There was a short break of about 1 min between blocks. At first, considering that children can sustain attention for less time than adults, we set fewer trials for children. In Experiment 1a, children groups completed 64 trials (4 blocks), and the adult group finished 128 trials (8 blocks) of letter-like stimulus discrimination. In Experiment 1b, we chose a moderate number of trials, that is, 96 trials (4 blocks) of arrow-triangle stimulus discrimination, for all age groups. The procedure for Experiment 2 was the same as for the adults in Experiment 1a.

In Experiment 3, to control the task difficulty, the duration of stimuli was modulated individually to make the mean accuracy around 79% using a 3-up-1-down staircase procedure (Wetherill & Levitt, 1965).

The stimuli duration in each trial was determined by a 3-up-1-down staircase procedure, with 79% correct performance level (see Supporting Information for details). The average target duration of the participants in Experiment 3 was 50 ms ($SD = 11$ ms). Otherwise, the procedure for stimulus presentation and the block design was the same as those for adults in Experiment 1. Stimulus presentation and data acquisition were performed using a customized program written in Matlab (MathWorks, Natick, MA) using Psychtoolbox (Brainard, 1997).

Results

Experiment 1

In Experiment 1a, letter-like figures (“E,” “S,” “P,” and “d”) were used to explore the performance of the topological and nontopological discrimination in the central and peripheral visual fields for child and adult groups. Considering a potential confound that younger children in China may be unfamiliar with these shapes of letters in the Roman alphabet, we used geometrical forms (e.g., “△,” “∇”) as stimuli in Experiment 1b. For both Experiments 1a and 1b, we control for other potential confounding factors (e.g., area, luminance, overall size, stroke width, the number of lines and spatial frequency).

Table 2 reports mean correct RTs and accuracy for each age group in Experiments 1a. The RTs for correct responses were analyzed. The statistical results of raw RTs are given in Supporting Information (Tables S1–S3). The correct RTs for each participant were filtered before analysis by removing values that were shorter than 150 ms or longer than 3 SD across all correct trials for each participant, leading to a small proportion of removal of measured RTs (Experiment 1a: 3.5%; Experiment 1b: 2.0%; Experiment 2: 1.4%; Experiment 3a: 0.6%; Experiment 3b: 1.2%). Data from participants whose mean RTs were more than 3 SD s from the average of their age groups were excluded from further analysis (Experiment 1a: 1.2% [6 year: 2.1%; 8 year: 1.0%; 10 year: 0%; 12 year: 1.4%; 14 year: 1.0%; adults:

0%]; Experiment 1b: 0.7% [6 year: 3.3%; other age groups: 0%]; Experiment 2: 0%; Experiment 3: 0%).

Normalized RTs (z-Scores)

As shown in Table 2, RTs declined with age, that is, shorter RTs were found in the older age groups, with a maximum difference in RT of more than 600 ms between 6-year-olds and adults. To compare the TP priority effect across age groups, RTs were normalized into z-scores for each participant separately. It should be noted that the relative magnitude between RTs for each condition remained constant for each participant during the within-subject normalization. In Experiment 1a and 1b, we used a three-way analysis of variance (ANOVA) on the normalized RTs to examine the between-subject factor age group and the two within-subject factors eccentricity (central and peripheral) and discrimination type (TP and non-TP). In Experiment 1a, as show in Table 3, all three factors showed significant main effects. The normalized RTs increased with eccentricity ($F(1, 607) = 420.27, p < .001, \eta_p^2 = .409$), RTs were shorter for TP discrimination than non-TP discrimination ($F(1, 607) = 92.30, p < .001, \eta_p^2 = .132$), and were different between age groups ($F(5, 607) = 75.22, p < .001, \eta_p^2 = .383$). The two-way interaction between age group and eccentricity as well as between age group and discrimination type were both significant (Age Group \times Eccentricity: $F(5, 607) = 23.22, p < .001, \eta_p^2 = .161$; Age Group \times Discrimination Type: $F(5, 607) = 14.23, p < .001, \eta_p^2 = .105$), however, no significant interaction occurred between eccentricity and discrimination type ($F(1, 607) = 0.38, p = .538, \eta_p^2 = .001$). The three-way interaction was significant ($F(5, 607) = 3.04, p = .01, \eta_p^2 = .024$). Due to the significant interactions and because the purpose of the experiment to test whether the development of the TP priority is different in the central and peripheral vision, we then performed simple main effect analyses with Bonferroni correction to examine the effects of age group and discrimination type in

Table 2

Mean Correct Reaction Times (RTs) and Accuracy Scores for Each Age Group in Experiment 1a. The Number of Valid Data for Each Age Group Was Given. Standard Errors of the Mean Are Also Reported

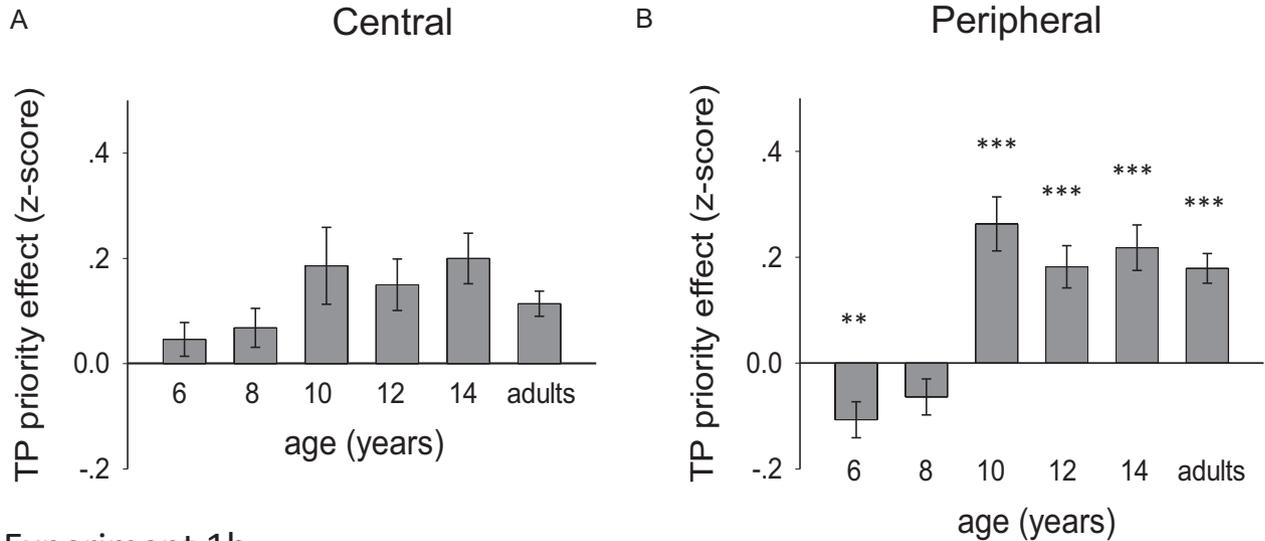
Age group	6 (N = 138)	8 (N = 103)	10 (N = 49)	12 (N = 136)	14 (N = 93)	Adults (N = 94)
RTs (ms) (SE)	1,076.40 (16.09)	734.13 (18.62)	670.27 (27.00)	530.04 (16.21)	487.53 (19.60)	428.63 (19.50)
Accuracy (%) (SE)	86.49 (0.68)	92.49 (0.79)	94.52 (1.14)	92.76 (0.69)	94.09 (0.83)	97.47 (0.82)

Table 3
Results of the Three-Way Analysis of Variance on the Normalized Reaction Times From Experiment 1a

Analysis and dependent variable	F	p	η_p^2
Discrimination type	93.30	< .001	.132
Eccentricity	420.27	< .001	.409
Age group	75.22	< .001	.383
Age Group \times Eccentricity	23.22	< .001	.161
Age Group \times Discrimination Type	14.23	< .001	.105
Eccentricity \times Discrimination Type	0.38	.538	.001
Eccentricity \times Discrimination Type \times Age Group	3.04	.010	.024

central and peripheral conditions, respectively. For central vision (Figure 2A), the main effects of age group and discrimination type were both significant (age group: $F(5, 607) = 36.04, p < .001, \eta_p^2 = .229$; discrimination type: $F(1, 607) = 46.29, p < .001, \eta_p^2 = .071$), suggesting the TP priority effect in the central visual field. The interaction between age group and discrimination type failed to reach significance ($F(5, 607) = 2.06, p = .069, \eta_p^2 = .017$), indicating that the TP priority effect in central visual field did not differ significantly among age groups. For peripheral vision (Figure 2B), the main effects of

Experiment 1a



Experiment 1b

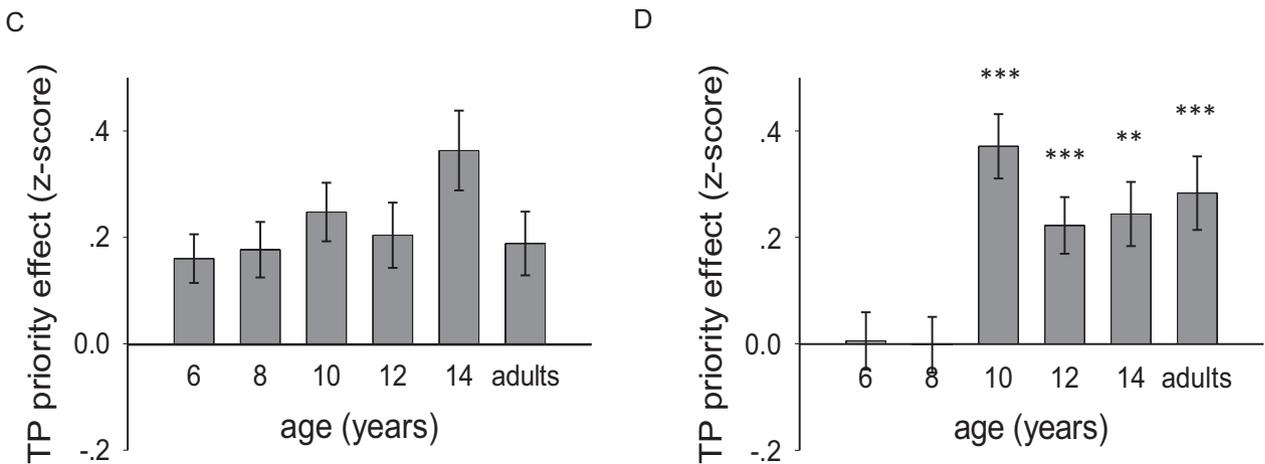


Figure 2. Normalized TP priority effects. Mean normalized TP priority effects for the central and peripheral vision for each age group in Experiment 1a (A and B) and 1b (C and D). Normalized TP priority effects (z-score) were computed from the normalized reaction time differences between non-TP and TP trials. Error bars show SEM values. TP = topological property. ** $p < .01$. *** $p < .001$.

age group and discrimination type and their interaction were all significant (age group: $F(5, 607) = 9.13$, $p < .001$, $\eta_p^2 = .070$; discrimination type: $F(1, 607) = 44.67$, $p < .001$, $\eta_p^2 = .069$; the interaction: $F(5, 607) = 16.67$, $p < .001$, $\eta_p^2 = .121$). We performed further posthoc analyses with Bonferroni correction for peripheral vision to compare differences between TP and non-TP discrimination, that is, the TP priority effect, in different age groups. As shown in Figure 2B, the TP priority effect was significant for participants in all age groups 10 years and older (10 years: $t(48) = 4.70$, $p < .001$, Cohen's $d = 0.730$; 12 years: $t(135) = 5.52$, $p < .001$, Cohen's $d = 0.391$; 14 years: $t(92) = 5.45$, $p < .001$, Cohen's $d = 0.528$; adults: $t(93) = 4.48$, $p < .001$, Cohen's $d = 0.650$). In contrast, the two younger age groups (6 and 8 years) showed a trend opposite to TP priority. Instead of shorter RTs for TP discrimination than for non-TP discrimination, participants in these two age groups seemed to show a superiority for non-TP discrimination (6 years: $t(137) = 3.24$, $p = .001$, Cohen's $d = 0.266$; 8 years: $t(102) = 1.68$, $p = .097$, Cohen's $d = 0.186$). These results suggest that children younger than 8 years have not yet developed their TP priority abilities for topological discrimination of peripheral stimuli.

Similar results were observed in Experiment 1b. All three factors showed significant main effects (age group: $F(5, 278) = 2.69$, $p = .021$, $\eta_p^2 = .046$; eccentricity: $F(1, 278) = 61.82$, $p < .001$, $\eta_p^2 = .182$; discrimination type: $F(1, 278) = 121.47$, $p < .001$, $\eta_p^2 = .304$). The two-way interactions were significant between age group and eccentricity ($F(5, 278) = 9.40$, $p < .001$, $\eta_p^2 = .145$), and between age group and discrimination type ($F(5, 278) = 5.49$, $p < .001$, $\eta_p^2 = .090$); but was not significant between eccentricity and discrimination type ($F(1, 278) = 1.33$, $p = .249$, $\eta_p^2 = .005$). The three-way interaction was significant ($F(5, 278) = 3.35$, $p = .006$, $\eta_p^2 = .057$). It should be noted that the three-way interaction did not reach significance ($F(5, 191) = 1.18$, $p = .319$, $\eta_p^2 = .030$) with the original sample size of 198. Similar to Experiment 1a, we then performed simple main effect analyses to examine the effects of age group and discrimination type in central and peripheral conditions, respectively. For central vision (Figure 2C), the main effects of age group and discrimination type were both significant (age group: $F(5, 278) = 9.39$, $p < .001$, $\eta_p^2 = .144$; discrimination type: $F(1, 278) = 86.92$, $p < .001$, $\eta_p^2 = .238$). There was also no significant interaction between age group and discrimination type ($F(5, 278) = 1.36$, $p = .241$, $\eta_p^2 = .024$), indicating that the TP priority effect in central visual field was similar for different age

groups. For peripheral vision (Figure 2D), the main effects of age group and discrimination type and their interaction were all significant (age group: $F(5, 278) = 9.26$, $p < .001$, $\eta_p^2 = .143$; discrimination type: $F(1, 278) = 57.68$, $p < .001$, $\eta_p^2 = .172$; the interaction: $F(5, 278) = 7.68$, $p < .001$, $\eta_p^2 = .121$). Further posthoc analyses with Bonferroni correction were performed for peripheral vision to examine the TP priority effect for all age groups. As shown in Figure 2D, the TP priority effect was significant for participants in all age groups 10 years and older (10 years: $t(46) = 6.29$, $p < .001$, Cohen's $d = 1.444$; 12 years: $t(41) = 3.60$, $p < .001$, Cohen's $d = 0.903$; 14 years: $t(30) = 3.38$, $p = .002$, Cohen's $d = 1.096$; adults: $t(38) = 4.42$, $p < .001$, Cohen's $d = 0.985$). In contrast, no significant TP priority effects were found for 6- and 8-year-olds (6 years: $t(57) = 0.11$, $p = .914$, Cohen's $d = 0.021$; 8 years: $t(66) = -0.06$, $p = .952$, Cohen's $d = -0.009$).

Accuracy

As shown in Table 2, performance for these age groups was good, with the average accuracy of above 93%. Nevertheless, the mean accuracy for the 6-year-old group (about 86%) was a little lower than other groups, suggesting that the discrimination task may have been more difficult for 6-year-old children. The question of task difficulty will be studied in Experiment 3. Detailed statistical results are presented in Supporting Information (Tables S4–S6). In short, the accuracy results show no evidence of speed-accuracy trade-offs.

To summarize, with either letter or geometrical stimuli, similar findings were obtained that the TP priority effect in peripheral vision did not emerge until age ~10 years whereas there were no significant differences between age groups in central vision, suggesting a late development of a basic visual perception (i.e., TP perception) and a possible differentiation between the development of central and peripheral visual functions.

Experiment 2: Stimulus Size in the Central and Peripheral Visual Fields

Stimulus size influences RTs (Carrasco et al., 2003; Osaka, 1976). In Experiment 1, peripheral stimuli ($3^\circ \times 5.25^\circ$) were larger than central stimuli ($1^\circ \times 1.75^\circ$). Therefore, to test the possible effect of stimulus size on the performance we made central and peripheral stimuli equal in physical size ($2^\circ \times 3.5^\circ$) in Experiment 2. Except for the size of stimuli, the

stimulus design was identical to that of Experiment 1a. Eighteen adult participants took part in Experiment 2. RTs were entered into a two-way ANOVA with eccentricity and discrimination type as factors. As shown in Figure 3A, RTs were longer for peripheral stimuli than for central stimuli (central: 386 ms vs. peripheral: 466 ms; $F(1, 17) = 56.22, p < .001, \eta_p^2 = .768$), and RTs were shorter for TP discrimination than for non-TP discrimination (TP: 417 ms vs. non-TP: 435 ms; $F(1, 17) = 25.91, p < .001, \eta_p^2 = .604$). There was no significant interaction ($F(1, 17) = 2.24, p = .153, \eta_p^2 = .116$).

We then compared the results from Experiment 2 with those obtained for the adult group during Experiment 1a (Figure 3B). A three-way ANOVA was applied to the RT data of the two experiments, with eccentricity and discrimination type as within-subject factors, and the two experiments as a between-subject factor. The average RTs of the two experiments were not significantly different ($F(1, 110) = 0.01, p = .914, \eta_p^2 < .0001$). Similarly, RTs were also increased with eccentricity ($F(1, 110) = 100.21, p < .001, \eta_p^2 = .477$), and RTs were shorter for TP discrimination than for non-TP discrimination ($F(1, 110) = 26.96, p < .001, \eta_p^2 = .197$). The only significant interaction was between eccentricity and the two experiments ($F(1, 110) = 36.55, p < .001, \eta_p^2 = .249$), and there were no other significant interactions (Discrimination Type \times Experiments: $F(1, 110) = 0.55, p = .460, \eta_p^2 = .005$; Discrimination Type \times Eccentricity: $F(1, 110) = 3.21, p = .076, \eta_p^2 = .028$). Additional simple main effect analysis showed that RTs for peripheral stimuli were slightly longer for Experiment 2 than for Experiment 1a ($t = 1.04,$

$p = .301, \text{Cohen's } d = 0.188$), whereas RTs for central stimuli were slightly shorter for Experiment 2 than for Experiment 1a ($t = 1.45, p = .151, \text{Cohen's } d = 0.382$). These results suggest that at the same eccentricity, the bigger the stimulus, the faster the response. Importantly, the TP priority effects were not affected by the physical size of the stimulus.

The mean accuracy in Experiment 2 was 96.77%, which was not different from the accuracy score of adults in Experiment 1a ($F(1, 110) = 1.80, p = .182, \eta_p^2 = .016$). The accuracy for peripheral stimuli was significantly lower than that for central stimuli when peripheral stimuli were reduced to the same size as central stimuli. ($F(1, 17) = 10.03, p = .006, \eta_p^2 = .371$). The difference between the accuracy for TP (97.3%) and non-TP (96.3%) discrimination failed to reach significance ($F(1, 17) = 3.13, p = .095, \eta_p^2 = .155$), and there was no speed-accuracy trade-off. Detail statistical results of accuracy are presented in Supporting Information (see Table S7).

Experiment 3: Task Difficulty

The lower accuracy (about 86%) of 6-year-old children compared to other groups (above 92%) in Experiment 1 suggests that task difficulty could be a confounding factor. In Experiment 3, we increased task difficulty for adults. The duration of stimuli was modulated individually to make the mean accuracy around 79% by using a 3-up-1-down staircase procedure (Wetherill & Levitt, 1965). Otherwise, we repeated Experiment 1. The mean accuracy was 83.37% for Experiment 3a and 85.49% for Experiment 3b, which were both slightly

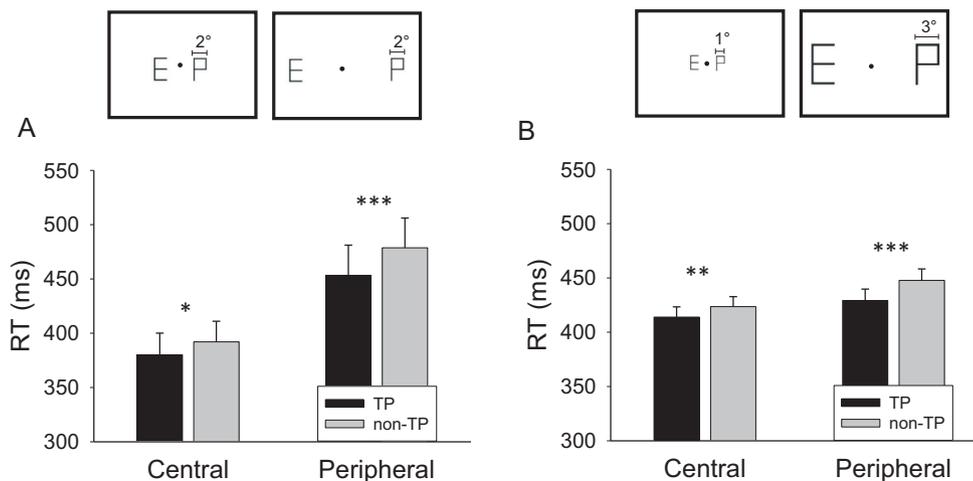


Figure 3. Results of Experiment 2 compared with adult results in Experiment 1a. Mean RTs of Experiment 2 (A) and RTs of adults in Experiment 1a (B). TP = topological discrimination, non-TP = nontopological discrimination. Error bars show SEM values. RT = reaction time; TP = topological property.

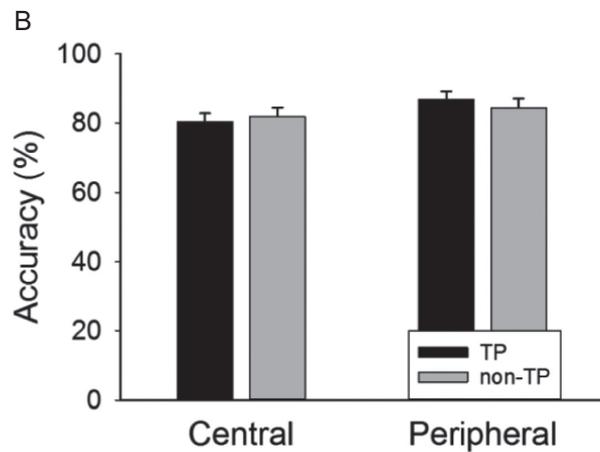
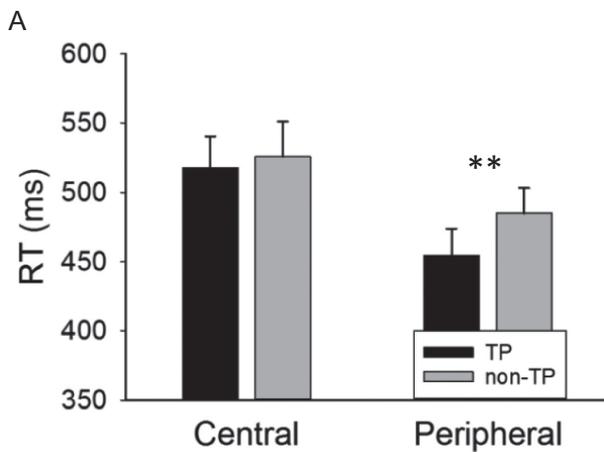
* $p < .05$. ** $p < .01$. *** $p < .001$.

lower than the mean accuracy of 6-year-old children in Experiment 1. RTs were entered into a two-way ANOVA with eccentricity and discrimination type as factors for Experiment 3a and 3b, respectively. In Experiment 3a (Figure 4A), shorter RTs for TP discrimination than non-TP discrimination ($F(1, 13) = 14.25, p = .002, \eta_p^2 = .523$), suggesting that the TP priority effect remained robust even when the task became more difficult. Different from Experiment 1, the RTs were shorter for peripheral stimuli than for central stimuli ($F(1, 13) = 19.22, p = .001, \eta_p^2 = .597$). The interaction was not significant ($F(1, 13) = 3.91, p = .07, \eta_p^2 = .231$). Similar results were found for Experiment 3b (Figure 4C). The main effects of the two factors

were both significant (eccentricity: $F(1, 13) = 18.15, p = .001, \eta_p^2 = .583$; discrimination type: $F(1, 13) = 14.09, p = .002, \eta_p^2 = .520$), and the interaction was not significant ($F(1, 13) = 1.22, p = .29, \eta_p^2 = .086$). These results indicated that the TP priority effect was unaffected by task difficulty. Thus, the disappearance of the TP priority effect in the peripheral visual field observed with 6-year-old children cannot be attributed to task difficulty.

The accuracy of peripheral stimuli was a little higher than that of central stimuli (In Experiment 3a, central: 81.1% versus peripheral: 85.6%; in Experiment 3b: central: 81.9% versus peripheral: 88.9%), indicating the task was more difficult for

Experiment 3a



Experiment 3b

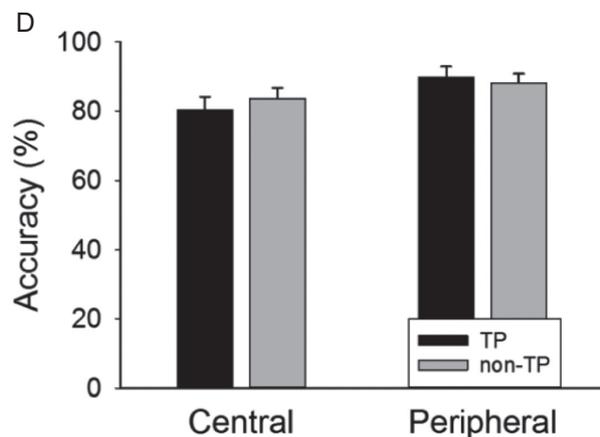
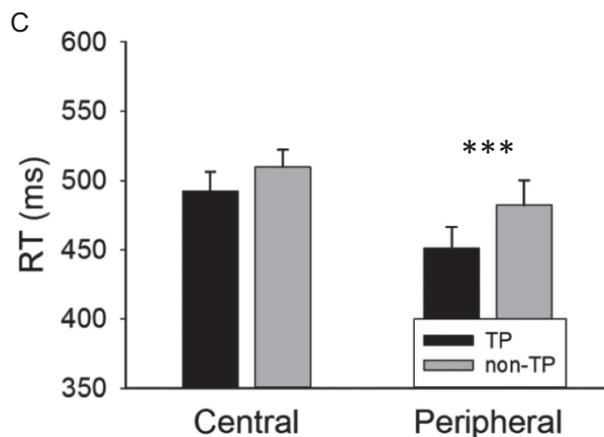


Figure 4. Results of Experiment 3. Mean RTs and accuracy scores in Experiment 3a (A and B) and 3b (C and D). TP = topological discrimination, non-TP = nontopological discrimination. Error bars show SEM values. RT = reaction time; TP = topological property. ** $p < .01$. *** $p < .001$.

central stimuli, consistent with the RT finding, that is, longer RTs for central stimuli. As shown in Figures 4B and 4D, the accuracy for TP discrimination had no difference from that for non-TP discrimination (Experiment 3a: $F(1, 13) = 0.06$, $p = .818$, $\eta_p^2 = .004$; Experiment 3b: $F(1, 13) = 0.15$, $p = .703$, $\eta_p^2 = .012$), suggesting no speed-accuracy trade-offs. Detail statistical results of accuracy are given in Tables S8 and S9.

Discussion

Previous evidence shows that the global TP is processed prior to other geometric properties (e.g., Huang et al., 2011, 2018). This study sought to investigate how this “global-first” develops during childhood. We investigated the performance of 773 children aged 6 to 14 years, as compared to adults, in a TP and non-TP discrimination task. Potential confounding factors for TP discrimination, for example, luminance, size, and the number of lines, were controlled and matched between different stimuli. In addition to letter-like stimuli, we also used geometric stimuli, that is, arrow-triangle figures, to examine whether effects depended on the use of letter-like forms whose familiarity may have changed with age. The results revealed that adults and children ≥ 10 years old showed a TP priority effect in both their central and peripheral visual fields, that is, they processed TP differences faster than non-TP differences. Children aged 6–8 years showed a different TP-processing pattern, that is, the TP priority effect has not been fully demonstrated at this age, which might be more apparent in their peripheral visual field compared with the central visual field.

According to previous research, the physical size of a stimulus could affect the processing speed (Carasco et al., 2003). To test whether the TP priority effect would be affected by the magnified peripheral stimuli, we made central and peripheral stimuli equal in physical size in Experiment 2. We observed that the decrease in peripheral stimulus size led to an increase in RTs, which is consistent with previous studies (e.g., Osaka, 1976). Nevertheless, the TP priority effect remained the same for the reduced peripheral stimulus, suggesting that the TP priority effect was not affected by the stimulus size.

There is a possibility that the lower accuracy of 6-year-old children would influence their performance on TP and non-TP discrimination speed, that is, the TP priority effect. This question was

investigated in Experiment 3. We found that the TP priority effect of adults was still robust even when the average accuracy was lower than that of the 6-year-old group. Therefore, task difficulty did not contribute to the present finding that 6- to 8-year-olds did not show the TP priority effect in peripheral vision.

In the field of vision research, the difference existing between central and peripheral vision is a rule rather than an exception (Masland, 2017; Rosenholtz, 2016). For example, the central vision has good acuity and color perception, whereas peripheral vision does not due to a sharp decline of cones as eccentricity increases (Anderson, Mullen, & Hess, 1991; Strasburger, Rentschler, & Jüttner, 2011). Even homogenous photoreceptor cells in central and peripheral regions of the retina may respond differently to incoming photons. A recent study reports that peripheral cones respond to light twice as fast as cones in the central visual field (Sinha et al., 2017). A possible explanation is that information from the central and peripheral fields arrives at higher-level brain areas via different routes (Stephen et al., 2002). In this study, however, we found that peripheral discrimination was slower than that of the central field for both TP and non-TP differences in Experiments 1 and 2. The slower processing speed in peripheral vision compared to central vision has also been reported in previous studies for both simple stimulus-onset detection and more complex reading tasks (Ando, Kida, & Oda, 2001; He, Baek, & Legge, 2018). Interestingly, when the stimulus presentation time was reduced, that is, when the task became difficult, on the contrary, we found that the response of peripheral stimuli was faster than that of central stimuli. This surprising finding suggests that the response speed of central and peripheral vision will be differentially affected by the difficulty of the task, and compared with central vision, peripheral vision has more advantages in processing short-term stimulation. We will continue to study this issue in follow-up work.

In addition to differences in the anatomical structure and function, there are also differences in the development of central and peripheral vision. An anatomical study found that rod photoreceptors in the peripheral retina develop earlier than those located more centrally on the retina, and parafoveal cones develop ahead of central ones (Hendrickson & Drucker, 1992). Evidence also shows that the central and peripheral visual functions develop at different speeds (Braddick & Atkinson, 2011). Moreover, the present findings suggest that not only does central and peripheral vision develop at different rates, but

also their functional modes could be entirely different during some developmental stages. When the advantage of TP processing over non-TP processing first emerges in the central visual field for children aged between 6 and 8 years, their peripheral vision still does not show a TP advantage or could even be a disadvantage, which suggests different development paths for topological perception in central and peripheral vision. Peripheral vision is usually characterized by the rapid response to survival-related information and could be related to a conservative processing channel. For example, Bayle, Henaff, and Krolak-Salmon (2009) have suggested that peripheral vision is associated with rapid fear detection. Thus, we were surprised to find that perception develops relatively late for the peripheral visual function. The development characteristics of the TP priority into development indicated that central and peripheral visions have their strengths and limitations, which are related to their different visual functions.

Substantial evidence from previous studies has shown the TP processing priority (He et al., 2015; Huang et al., 2011, 2018; Meng et al., 2018). Topological invariants during shape transformations include closure (or holes), connectivity and the inside/outside relation (Chen, 2005). For instance, He et al. found that the primitive units counted in numerosity perception are defined by TP, such as connectivity and the inside/outside relation (He et al., 2015). Chen's topological perception theory (1982, 2005) suggests that topological properties are extracted as basic primitives in object perception and modulate the ongoing visual processing of other properties. Closure and connectivity as primitives of visual form perception have also been proposed by other researchers, for example, in the texton theory proposed by Julesz (1981). Topology, a branch of mathematics, well connects these seemingly independent attributes and defines the primitives at the early stage of vision.

A subcortical hypothesis has been proposed, positing that topological perception is processed through a Superior Colliculus (SC)-Pulvinar-Amygdala subcortical pathway, which is considered to be relatively conserved across different species and responsible for the rapid information processing (Sun et al., 2019; Wei et al., 2015). This subcortical hypothesis is supported by direct evidence from a human brain imaging study which showed that the TP "hole" was processed in the SC and physiological evidence from a mouse study (Huang et al., 2020; Meng et al., 2018). The hypothesis is also supported by indirect evidence from a transcranial magnetic stimulation (TMS) study (Du, Zhou, & Chen, 2011), showing that

early-stage TP processing was unaffected when the primary visual cortex (V1) was blocked by TMS, which suggests that the TP could be processed through a subcortical pathway not passing through V1. We can also learn about the function development of the subcortical pathway through this study. As peripheral vision is more closely related to subcortical processing (Bayle et al., 2009), the present finding of late development of peripheral vision in TP perception suggests that the subcortical visual pathway for TP processing may not be immutable from birth, instead, this pathway undergoes development into middle childhood.

Although many aspects of children's visual development have been reported to continue until late childhood, for example, global form perception and depth cues integration (Dekker et al., 2015; Lewis et al., 2004), the late maturation of the TP priority effect (about the age of 9–10 years) is still surprising. As mentioned in the introduction, even newborns possess the ability to discriminate between topological differences in figures (Lin et al., 2016). One possible explanation is that topological discrimination ability develops separately from reaction speed, which is the main indicator in this study.

Although many potential confounding factors between the TP and non-TP discrimination conditions, such as luminance, size, the number of lines, spatial frequency, familiarity with letter shapes and the orientation of the diagonal line segment of arrow and triangle stimuli, were controlled and matched, there are still some confounding factors that have not been completely ruled out in this study. For example, the difference in the shift of vertical line segments between the letter stimuli and the difference in the shape of the "convex hull" between the arrow and triangle stimuli were not totally excluded, which needs further work to address.

The TP discrimination tests provide a unique window into the development of the early stages of visual processing in children. The present results show the late development of global topological perception, which increases our understanding of visual-function development. Furthermore, these results highlight questions related to the relations in the development of the central and peripheral visual systems. Our unpublished studies showed that the abnormality of TP perception is associated with some brain diseases such as schizophrenia and autism. Therefore, research on children's TP perception and establishment of the corresponding norms for children of different ages may prove helpful for early and objective diagnosis of these diseases.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Table S1. Results of Three-Way Analysis of Variance for Raw Reaction Times From Experiment 1a

Table S2. Simple Main Effect Analyses of Each Age Group for Raw Reaction Times From Experiment 1a

Table S3. Results of the Three-Way Analysis of Variance on the Raw Reaction Times From Experiment 1b

Table S4. Results of the Three-Way Analysis of Variance on Accuracy Scores in Experiment 1a

Table S5. Simple Main Effect Analyses of Each Age Group for Accuracy in Experiment 1a

Table S6. Results of the Three-Way Analysis of Variance on Accuracy Scores in Experiment 1b

Table S7. Results of the Two-Way Analysis of Variance on Accuracy Scores in Experiment 2

Table S8. Results of the Two-Way Analysis of Variance on Accuracy Scores in Experiment 3a

Table S9. Results of the Two-Way Analysis of Variance on Accuracy Scores in Experiment 3b