Age-related changes in local and global visual perception

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Over the past 40 years, research has addressed the impact of the aging process on various aspects of visual function. Most studies have focused on age-related visual impairment in low-level local features of visual objects, such as orientation, contrast sensitivity and spatial frequency. However, whether there are lifespan changes in global visual perception is still unclear. To suitably frame this question, we defined global visual

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patterns by a topological approach, and local visual patterns were manipulated with different levels of geometrical invariants in descending order of structural stability from projective, affine, and then Euclidean features. Using the Configural Superiority Effect, we investigated the influence of aging on local and global visual perception through a comparison of young and old adults in Experiment 1; moreover, we provided continuous-aging data from 21 to 78 years of age to investigate age-related changes in visual perception in Experiment 2. We found a large perceptual decline across increasing age groups in local geometrical perception: for example, Euclidean (orientation), affine (parallelism), and projective (collinearity) discrimination. Moreover, the study provides a counterintuitive finding that global topological perception resists the aging process and remains constant throughout adult lifespan. These findings highlight the possibility that for humans, global topology may be a stable and fundamental component by which visual systems represent and characterize objects.

Introduction

The global elderly population has grown over the last 40 years and an increasing number of studies have focused on aging-related changes in the human visual system. The scientific spotlight has focused not only on the effects of aging on eye conditions and diseases (for example, macular degeneration, glaucoma, and diabetic retinopathy; Curcio, Medeiros, & Millican, 1996; Eisner, Klein, Zilis, & Watkins, 1992; Jackson, Curcio, Sloan, & Owsley, 2004; Jackson & Edwards, 2008; Matthew et al., 2005; Medeiros & Curcio, 2001; Starita, Hussain, Pagliarini, & Marshall, 1996; Sunness et al., 2008; Vinding, 1990) but also on understanding how the aging process impacts various aspects of visual function and task performance.

It is well established that older adults show a perceptual deterioration in the detection of low-level local features of objects, such as orientation, contrast sensitivity, and spatial frequencies (Derefeldt, Lennerstrand, & Lundh, 1979; D. B. Elliott, Whitaker, & MacVeigh, 1990; S. L. Elliott et al., 2009; Kline, 1987; Kline & Schieber, 1985; Kline, Schieber, Abusamra, & Coyne, 1983; Owsley, Sekuler, & Siemsen, 1983; Ross, Clarke, & Bron, 1985; Tulunay-Keesey, VerHoeve, & Terkla-McGrane, 1988). In addition, it has been suggested that aging eye conditions (pupillary miosis, increased lens density, increased intraocular light scatter, and increased aberrations) partly contribute to the loss of these local visual functions in older adults (Artal, Guirao, Berrio, Piers, & Norrby, 2003; Atchley, & Anderson, 1998; Glasser & Campbell, 1998; Loewenfeld, 1979; Pokorny, Smith, & Lutze, 1987; Said & Weale, 1959; Weale, 1961). However, it has not yet been determined whether there are age-related changes in the perception of global visual patterns. Traditionally, global visual function is described by Gestalt theory; however, Gestalt evidence has often been criticized for being somewhat subjective (Pomerantz, 2003). When investigating visual perception, precise definitions of the terms global and local are required. A "Global-first" theory with a topological approach provides such a definition of global versus local visual perception and also a new perspective in the understanding of global versus local relationships (Chen, 1982, 2005; Huang et al., 2018; Huang, Zhou, & Chen 2011; Wang, Zhou, Zhuo, & Chen, 2007; Zhuo et al., 2003; Zhou, Luo, Zhou, Zhuo, & Chen, 2010). The topological properties of an image have a holistic identity that remains constant across various smooth shape image transformations. These shape transformations can be imagined as continuous deformations of a rubber sheet, such as bending or stretching, but not tearing apart or gluing parts together. In this kind of rubber-sheet distortion, the number of holes remains unchanged and, therefore, is a topological property (Chen, 1982, 2005). A property is considered more global (or stable) when the more general the transformation group is, the more the property remains invariant. The global topological property that is the number of holes (hereafter referred to as holes) is structurally more stable than local properties (for example, Euclidean, affine, and projective).

In this study, to better understand the role of lifespan changes in global and local visual perception, perception was examined according to different levels of structural stability. Specifically, global visual information was defined by a topological approach, whereas local visual perception was manipulated by different levels of geometrical invariants, such as Euclidean, affine, and projective properties. The first experiment was performed to compare global and local perceptual changes between young and old adults. The second experiment was performed to investigate the trend of age-related changes in global and local visual perception over the entire adult lifespan, from 21 to 78 years of age.

Experiment 1

Methods

Ethics statement

The experiment was performed according to the principles expressed in the Declaration of Helsinki and was approved by the Human Research Ethics Committee of the Institute of Biophysics, Chinese Academy of Sciences. All participants provided written informed consent for the collection of data and subsequent analysis.

Participants

Eighteen healthy young adults (10 males, eight females) from the age of 25 to 35 years and 18 healthy older adults (nine males, nine females) from the age of 65 to 72 years were recruited through advertisement and paid to participate. No participant had any history of psychiatric illness, neurological illness, use of antiepileptic medications, or drug/alcohol abuse. All participants had normal or corrected-to-normal vision and were all right-handed.

Visual acuity (VA) was determined for both left and right eyes using the International Standard Visual Acuity Chart displayed with a standard illumination box at a distance of 5 m and dominant eye measurements were chosen to represent individual visual acuity. The results were converted to logMAR visual acuity. The average logMAR VA was 0.90 ± 0.51 for the young group and 0.85 ± 0.38 for the old group.

Stimuli and procedure

Five stimulus arrays were designed to measure global and local perceptual responses using the "Configural Superiority Effect" paradigm. The configural superiority effect refers to findings that global configural relations between simple components, rather than the components themselves, may play a preferential role in visual processing (Chen, 2005; Wang et al., 2007). Here, configural superiority effects were evaluated in an odd quadrant task, where participants were asked to report which quadrant differed from the other three, as illustrated in Figure 1A.

Figure 1Aa, b, and c represent local difference conditions. Figure 1Ad represents the global difference condition, and Figure 1Ae represents the control condition. In Figure 1Aa, the exact same component line segments were present in all quadrants; however, the odd quadrant contained an arrow with a different orientation, a type of Euclidean property. Figure 1Ab represents a discrimination task based on a difference in parallelism, which is a type of affine property. The orientation of the line segments in the odd quadrant differed from that of the other quadrants. Figure 1Ac represents a discrimination task based on a difference in collinearity, which is a kind of projective property. Here, three quadrants have straight lines, whereas the odd quadrant has a line with one bend along its length, the length of which was the same as the straight lines. Figure 1Ad was adapted from Figure 1Aa; in the odd quadrant, the arrow was replaced with a triangle, which has the same three-line segments as the arrows but is

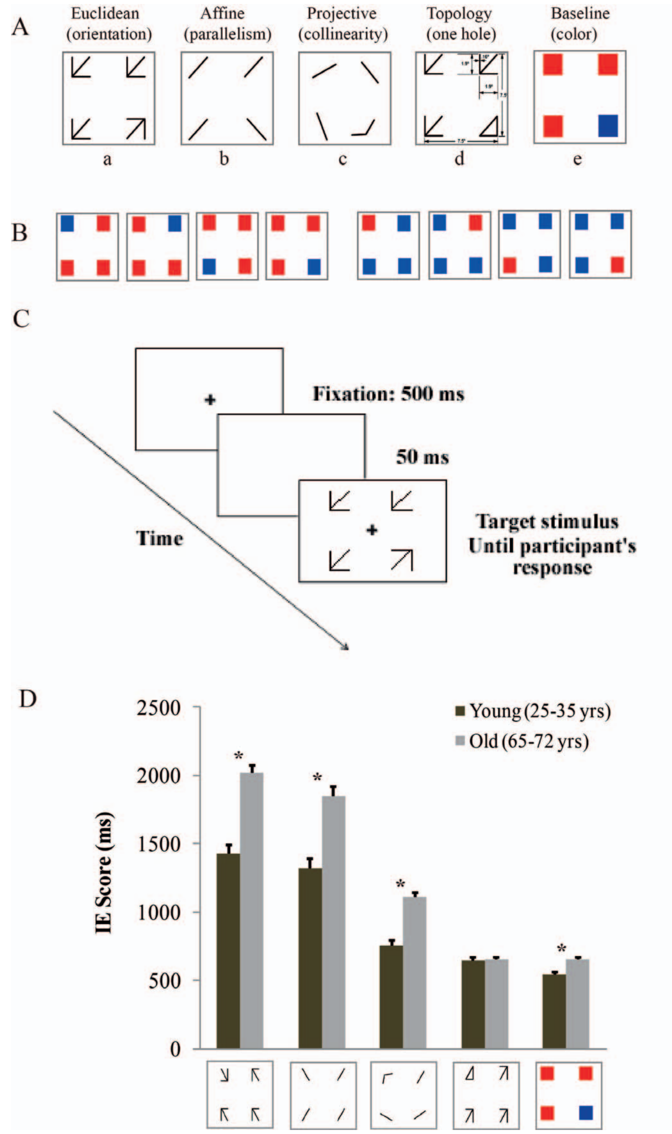

Figure 1. Stimuli, Procedures and Results of Experiment 1. (A) The stimulus arrays designed to measure the relative salience of the geometric invariants at different levels of structural stability in an odd quadrant task in Experiment 1. They represent discriminations based on (a) a difference in angle orientation, a kind of Euclidean property, (b) a difference in parallelism, a kind of affine property, (c) a difference in collinearity, a kind of projective property, (d) a difference in holes, a kind of topological property, and (e) a difference in color, a baseline stimulus. (B) Schematic illustration of stimulus pattern. (C) Flow diagram for Experiment 1. (D) Results of Experiment 1. Mean IE scores for old and younger adults in global topological (one hole) and local geometrical discrimination tasks (Euclidean: orientation; affine: parallelism; projective: collinearity). *$p < 0.001$.

topologically different from arrows due to its closed nature. In Figure 1Ae, the odd quadrant contains a different color than the other three, and this quadrant was used to establish a baseline due to it being the easiest task. Each stimulus type had eight different patterns and each pattern was presented three times (for example, as shown in Figure 1B).

MATLAB with Psychophysics Toolbox (MathWorks, Natick, MA) installed on a a Dell computer (OPTIPLEX 780) was used to present the stimuli (7.5° × 7.5°) on a 19-in. ViewSonic monitor (1024 × 768 pixel resolution, 100 Hz refresh rate). The average viewing distance was 58 cm.

Procedure

As illustrated in Figure 1C, each trial began with a 500 ms fixation cross (0.45° × 0.45°), followed by an empty screen for 50 ms. A target stimulus was then presented on a white background until the participant responded. Participants were asked to maintain eye fixation on the cross throughout the trial. For the purpose of responding to stimuli, participants were given a four-button box and were instructed to respond with their left and right index fingers and thumbs. Each button corresponded to a specific quadrant that was explained to each participant beforehand, and participants were asked to respond as accurately and quickly as possible by pressing one button. Incorrect responses were followed immediately with an audible beep that served as feedback. An interval of 1000 ms preceded the beginning of the following trial. Participants completed a total of 120 trials presented in a randomized order.

Results

Reaction times (RTs) of less than 150 ms or more than 3 *SD* from the mean in each condition for each individual were removed from the analysis (< 5%). Mean RTs and accuracy were analyzed for each condition.

The Mean RTs and accuracy were analyzed with a multivariate approach using a repeated-measures analysis of variance (ANOVA) that was carried out with the two age groups as between-subject factors and the five stimulus types: (a) Euclidean: orientation, (b) affine: parallelism, (c) projective: collinearity, (d) topology: hole, and (e) color as the within-subject factors.

For mean RTs, the main effects of the age group and stimulus type were both statistically significant: age group, $F(1, 34) = 46.6$, partial $\eta^2 = 0.58$, $p < 0.001$; stimulus type, $F(4, 136) = 556.54$, partial $\eta^2 = 0.94$, $p < 0.001$. Given a significant interaction between age group and stimulus type, $F(4, 136) = 33.92$, partial $\eta^2 = 0.5$, $p < 0.001$, further comparison analyses were performed separately for each stimulus type between the young and old groups. Compared with the young group, perceptual deficits were found in the old group in local geometrical and color discrimination for the three stimulus types, which were all statistically significant: Euclidean (orientation), $F(1, 34) = 51.29$, partial $\eta^2 = 0.6$, $p < 0.001$; affine (parallelism), $F(1, 34) = 33.54$, partial $\eta^2 = 0.5$, $p < 0.001$; projective (collinearity), $F(1, 34) = 55.91$, partial $\eta^2 = 0.62$, $p < 0.001$; color, $F(1, 34) = 17.54$, partial $\eta^2 = 0.34$, $p < 0.001$. No difference was found in the global topological discrimination tasks: topology (hole), $F(1, 34) = 0.016$, partial $\eta^2 = 0.001$, $p = 0.901$, between the two groups. Because the RTs of global topological discrimination are obviously shorter than those of local geometrical discrimination, one may argue that a ceiling effect could account for the excellent performance of global topological discrimination in older people. However, the baseline color discrimination control indicated that the easiest task was not immune to age-related perceptual deficits.

For accuracy, the main effect of the stimulus type was statistically significant: stimulus type, $F(4, 136) = 3.93$, partial $\eta^2 = 0.1$, $p = 0.005$; whereas the main effect of the age group was not significant: age group, $F(1, 34) = 0.41$, partial $\eta^2 = 0.01$, $p = 0.52$. The interaction between age group and stimulus type was not significant: $F(4, 136) = 0.4$, partial $\eta^2 = 0.01$, $p = 0.8$. No difference in accuracy was observed between young and old adults in the global topological, local geometrical, and color discrimination tasks: topology (hole), $F(1, 34) = 0.548$, partial $\eta^2 = 0.016$, $p = 0.464$; Euclidean (orientation), $F(1, 34) = 0.063$, partial $\eta^2 = 0.002$, $p = 0.803$; affine (parallelism), $F(1, 34) = 0.221$, partial $\eta^2 = 0.006$, $p = 0.641$; projective (collinearity), $F(1, 34) = 0.347$, partial $\eta^2 = 0.01$, $p = 0.56$; color, $F(1, 34) = 1.15$, partial $\eta^2 = 0.033$, $p = 0.291$.

The results of RTs revealed an age-related deficit in local geometrical discrimination task. However, to correct for the potential speed-accuracy trade-offs present in the data (André, 2017; Raymond & Marc, 2011), accuracy and RTs were combined in an inverse efficiency score (IE score), which is a standard way of combining RT and accuracy data into a single performance measure. This score was computed as the mean RT for each stimulus type divided by the accuracy (the proportion of correct responses for that condition).

The IE scores were also analyzed with the multivariate approach using repeated-measures analysis of variance (ANOVA) with the two age groups as between-subject factors and the five stimulus types as the within-subject factors. Subsequent pairwise comparisons were evaluated using Bonferroni correction. The main effects of the age group and stimulus type were both statistically significant: age group, $F(1, 34) = 47.2$, partial $\eta^2 = 0.58$, $p < 0.001$; stimulus type, $F(4, 136) = 532.27$, partial $\eta^2 = 0.94$, $p < 0.001$. Further posthoc analysis revealed, firstly, a statistically signif-

Age (year)	All N	Visual acuity	Mean (year)	SD (year)	Men N	Mean (year)	SD (year)	Women N	Mean (year)	SD (year)
21–25	15	0.90 ± 0.33	23.3	1.2	5	23.0	1.0	10	23.5	1.35
26–35	26	0.92 ± 0.41	29.3	3.2	15	29.7	3.3	11	28.8	3.0
36–45	29	0.83 ± 0.38	40.0	3.2	11	42.0	1.6	18	40.3	3.1
46–55	15	0.87 ± 0.47	51.9	2.5	6	50.8	1.8	9	52.9	2.7
56–65	25	0.85 ± 0.53	60.7	3.3	13	62.3	2.7	12	59.0	2.8
66–78	26	0.80 ± 0.51	68.6	3.6	14	69.4	2.4	12	67.7	4.6

Table 1. Participant characteristics sorted by age and sex. *Note*: $N =$ the number of participants in each group.

icant difference between the IES of the global topological discrimination of holes and local geometrical discrimination: Euclidean versus topology, $t(35) = 17.72$, $p < 0.001$; affine versus topology, $t(35) = 16.11$, $p < 0.001$; projective vs. topology, $t(35) = 8.4$, $p < 0.001$. Secondly, there was a superiority effect of collinearity over parallelism (affine versus projective), $t(35) = 17.05$, $p < 0.001$, and orientation (Euclidean vs. projective), $t(35) = 19.51$, $p < 0.001$. And thirdly, discrimination based on parallelism was faster than that based on orientation (Euclidean vs. affine), $t(35) = 3.3$, $p < 0.002$. The results revealed a functional hierarchy of visual perception that is remarkably consistent with the order of stability of different geometries. As the baseline of the easiest task, IE scores for color discrimination were remarkably lower than all other conditions (all ps $<$ 0.001).

Due to a significant interaction between age group and stimulus type, $F(4, 136) = 31.24$, partial $\eta^2 = 0.48$, $p < 0.001$, further comparison analyses were performed separately for each stimulus type between the young and old groups. Compared with the young group (as shown in Figure 1D), perceptual deficits were found in the old group in local geometrical discrimination for the three stimulus types, which were all statistically significant: Euclidean (orientation), $F(1, 34) = 51.29$, partial $\eta^2 = 0.6$, $p < 0.001$; affine (parallelism), $F(1, 34) = 33.54$, partial $\eta^2 = 0.5$, $p < 0.001$; projective (collinearity), $F(1, 34) = 55.91$, partial $\eta^2 = 0.62$, $p <$ 0.001. For the baseline task there was also a perceptual deficit in color discrimination in the old group compared to the young group: color, $F(1, 34) = 19.39$, partial $\eta^2 = 0.36$, $p < 0.001$. However, no difference was observed in the global topological discrimination task between the young and old groups: $F(1, 34) = 0.05$, partial $\eta^2 = 0.001$, $p = 0.824$. The results of Experiment 1 suggest an age-related deficit in local geometrical discrimination (Euclidean, affine, and projective) and color discrimination. However, the response of old group in global topological discrimination was as fast as that of the young group.

By comparing two age groups, Experiment 1 revealed a different aging effect on local and global visual discrimination. To better understand the continuous age-related changes in visual perception across the entire adult lifespan, 136 participants with an age range of 21 to 78 years took part in Experiment 2, using a similar stimulus set.

Experiment 2

Methods

Ethics statement

The experiment was performed according to the principles expressed in the Declaration of Helsinki and was approved by the Human Research Ethics Committee of the Institute of Biophysics, Chinese Academy of Sciences. All participants provided written informed consent for the collection of data and subsequent analysis.

Participants

Adults (136 total; 72 females, 64 males) aging from 21 to 78 were recruited through advertisement and paid to take part in the experiment. Participants were divided into six groups based on chronological age (Table 1). No participant had any history of psychiatric illness, neurological illness, use of antiepileptic medications, or drug/alcohol abuse. All participants had normal or corrected-to-normal vision and were all right-handed.

Stimuli and procedure

To generalize the results of Experiment 1, a new set of stimuli was designed for Experiment 2. As shown in Figure 2Aa, the first task used texture discrimination based on a difference in the orientation of angles, which is a type of Euclidean property. The odd quadrant contained angles with a different orientation from that in the other quadrants, although the same component line segments were present in all quadrants. Figure

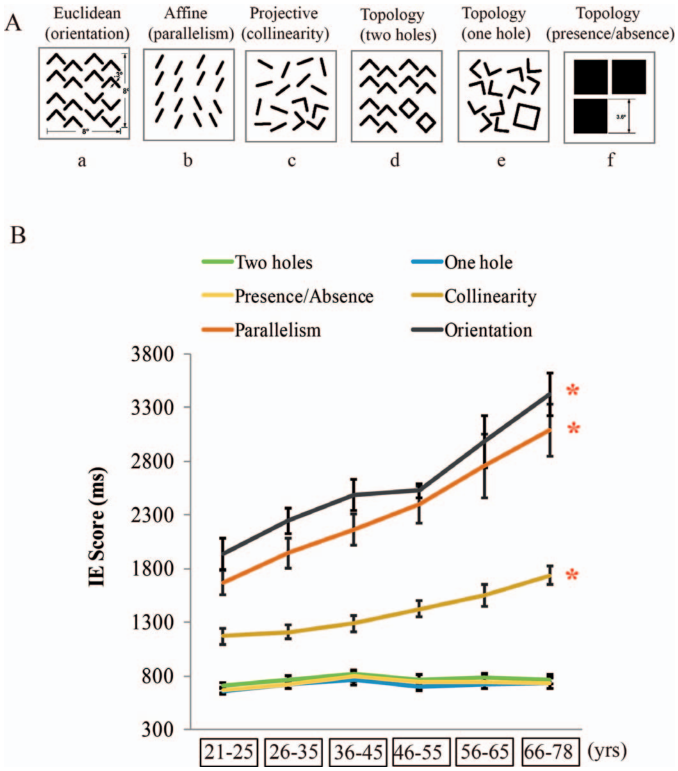

Figure 2. Stimuli and Results of Experiment 2. (A) The stimulus arrays designed to measure, in an odd quadrant task, the relative salience of the geometric invariants at different levels of structural stability in Experiment 2. They represent discriminations based on (a) a difference in angle orientation, a kind of Euclidean property, (b) a difference in parallelism, a kind of affine property, (c) a difference in collinearity, a kind of projective property, (d) a difference in holes, a kind of topological property (in the odd quadrant, four right angles form a larger square), (e) a difference in holes, a kind of topological property (in the odd quadrant, two of the four right angles are rotated 180° to join another two right angles to form two small squares), and (f) a difference in presence/absence, another kind of topological property. (B) Results of Experiment 2. Mean IE scores for participants over the adult life span from 21 to 78 years of age in global topological (two holes, one hole, and presence/absence) and local geometrical discrimination tasks (Euclidean: orientation; affine: parallelism; projective: collinearity). $^*p < 0.001$.

2Aa, b, and c represent local geometrical discrimination tasks, and Figure 2Ad, e, and f represented global topological discrimination tasks. Figure 2Ab represents a discrimination task based on a difference in parallelism, which is a type of affine property. Figure 2Ac represents a discrimination task based on a difference in collinearity, which is a kind of projective property. Here, three quadrants have straight lines in the same orientation, whereas the odd one has a line of the same length, but with one bend along its length. In Figure 2Ad, which was adapted from Figure 2Aa, three quadrants contained four separate lines with right angles, all aligned in the same direction and the odd quadrant contained two squares made by rotating two of the right angles by 180°. Figure 2Ae was designed so that the odd quadrant contained a larger square formed by four right angles, but the other quadrants each contained four right angles distributed in random orientations. Thus, Figure 2Ad and Figure 2Ae were both designed to represent a discrimination task based on holes. Figure 2Af was designed in such a way that the odd quadrant did not contain a shape, whereas the remaining quadrants each contained a large solid square. According to the topological theory, the presence or absence of an object may also be considered a kind of topological property because topological transformations neither create nor destroy objects. Therefore, despite their great differences in local features, the stimuli represented in Figure 2Ad, Figure 2Ae, and Figure 2Af share the same intrinsic topological differences. Experiment 2 tested two kinds of topological properties: holes and presence versus absence. Each stimulus type had eight different patterns and each pattern was presented three times. Participants completed a total of 144 trials presented in a randomized order.

The stimuli ($8.0° \times 8.0°$) were presented using the same set-up as in Experiment 1. The average viewing distance was 58 cm. Experiment 2 followed the same procedure as Experiment 1.

Results

RTs of less than 150 ms or more than three standard deviations from the mean in each condition for each individual were removed from the analysis (<3%). Mean RTs and accuracy were analyzed for each condition. The Mean RTs and accuracy were respectively analyzed with the multivariate approach using repeated-measures analysis of variance (ANOVA) that with the six age groups as between-subject factors and six stimulus types: (a) Euclidean: orientation, (b) affine: parallelism, (c) projective: collinearity, (d) topology: one hole, (e) topology: two holes, and (f) topology: presence/absence, as the within-subject factors.

For mean RTs, the main effects of the age group and stimulus type were both statistically significant: age group, $F(5, 130) = 7.4$, partial $\eta^2 = 0.22$, $p < 0.001$; stimulus type, $F(5, 650) = 374.99$, partial $\eta^2 = 0.74$, $p < 0.001$. Due to a significant interaction between age group and stimulus type, $F(25, 650) = 7.06$, partial $\eta^2 = 0.21$, $p < 0.001$, further comparison analyses were performed separately for each stimulus type between different aged groups. The results show that there is an age-related deficit in reaction time in local geometrical discrimination tasks: Euclidean (orientation), $F(5, 130)$

= 8.783, partial $\eta^2 = 0.253$, $p < 0.001$; affine (parallelism), $F(5, 130) = 7.065$, partial $\eta^2 = 0.214$, $p < 0.001$; projective (collinearity), $F(5, 130) = 6.567$, partial $\eta^2 = 0.202$, $p < 0.001$. However, for the global topological discrimination tasks, no difference was found between different aged groups: topology (hole), $F(5, 130) = 0.675$, partial $\eta^2 = 0.025$, $p = 0.643$; (two holes), $F(5, 130) = 0.64$, partial $\eta^2 = 0.024$, $p = 0.669$; (presence/absence), $F(5, 130) = 0.548$, partial $\eta^2 = 0.016$, $p = 0.464$.

For accuracy, the main effect of the stimulus type was statistically significant: (stimulus type), $F(5, 650) = 74.26$, partial $\eta^2 = 0.36$, $p < 0.001$; whereas the main effect of age group was not statistically significant: age group, $F(5, 130) = 0.99$, partial $\eta^2 = 0.037$, $p = 0.4$. No significant interaction between age group and stimulus type was obtained, $F(25, 650) = 0.78$, partial$\eta^2 = 0.03$, $p = 0.77$. No difference in accuracy was observed between different aged groups in global topological and local geometrical discrimination tasks: topology (hole), $F(5, 130) = 1.265$, partial $\eta^2 = 0.046$, $p = 0.283$; (two holes), $F(5, 130) = 1.048$, partial $\eta 2 = 0.039$, $p = 0.392$; (presence/absence), $F(5, 130) = 1.484$, partial $\eta^2 = 0.054$, $p = 0.2$; Euclidean (orientation), $F(5, 130) = 0.794$, partial $\eta^2 = 0.03$, $p = 0.556$; affine (parallelism), $F(5, 130) = 0.625$, partial $\eta^2 = 0.025$, $p = 0.658$; projective (collinearity), $F(5, 130) = 0.985$, partial $\eta^2 = 0.037$, $p = 0.4$.

The result of Experiment 2 was consistent with Experiment 1 that there was an age-related decline in RTs in local geometrical discrimination task, whereas no difference was obtained between different aged groups in global topological discrimination task. To correct for the potential speed-accuracy trade-offs present in the data, IE scores were also analyzed with a multivariate approach using repeated measures analysis of variance (ANOVA) that was carried out with the six age groups as between-subject factors and the six stimulus types as within-subject factors. Subsequent pairwise comparisons were evaluated with Bonferroni correction.

The main effects of the age group and stimulus type were both statistically significant: age group, $F(5, 130) = 7.42$, partial $\eta^2 = 0.22$, $p < 0.001$; stimulus type, $F(5, 650) = 424.34$, partial $\eta^2 = 0.77$, $p < 0.001$. Consistent with the order of stability of different geometries, results similar to those from Experiment 1 were obtained by further posthoc analysis. A statistically significant difference between global topological discrimination (hole and presence vs. absence) and local geometrical discrimination IES scores was found (all local geometrical properties vs. two holes, $p < 0.001$; all local geometrical properties vs. one hole, $p < 0.001$; all local geometrical properties vs. presence/absence, $p < 0.001$). The superiority effect of collinearity over parallelism and orientation and a superiority effect of parallelism over orientation were also observed in Experiment 2 (all ps < 0.001).

Due to a significant interaction between the age group and stimulus type, $F(25, 650) = 7.0$, partial $\eta^2 = 0.21$, $p < 0.001$, further analyses were performed separately for each stimulus type. Across age groups, a statistically significant perceptual loss in the local geometrical discrimination tasks: Euclidean (orientation), $F(5, 130) = 9.1$, partial $\eta^2 = 0.26$, $p < 0.001$; affine (parallelism), $F(5, 130) = 6.4$, partial $\eta^2 = 0.2$, $p < 0.001$; projective (collinearity), $F(5, 130) = 7.1$, partial $\eta^2 = 0.22$, $p < 0.001$, was obtained. However, no difference was observed in the global topological discrimination tasks: two holes, $F(5, 130) = 0.67$, partial $\eta^2 = 0.02$, p = 0.65; one hole, $F(5, 130) = 0.62$, partial $\eta^2 = 0.02$, $p = 0.68$; presence/absence, $F(5, 130) = 0.59$, partial $\eta^2 = 0.02$, $p = 0.71$.

Posthoc analyses were performed to compare the differences between age groups (as illustrated in Figure 2B). Multiple comparisons were evaluated using Bonferroni correction. For the local geometrical discrimination task, the oldest group of 66–78 years of age showed a large age-related perceptual deficit compared with that of the age groups of 21–25, 26–35, and 36–45 years (projective: 21–25 vs. 66–78, $p < 0.001$; 26–35 vs. 66–78, $p < 0.001$; 36–45 vs. 66–78, $p = 0.001$; affine: 21–25 vs. 66–78, $p < 0.001$; 26–35 vs. 66–78, $p = 0.001$; 36–45 vs. 66–78, $p = 0.009$; Euclidean: 21–25 vs. 66–78, $p < 0.001$; 26–35 vs. 66–78, $p < 0.001$; 36–45 vs. 66–78, $p = 0.001$). The older group of 56–65 years also showed a larger deficit in some local geometrical discriminations compared with that of the younger groups (projective: 26–35 vs. 56–65, $p = 0.04$; affine: 21–25 vs. 56–65, $p = 0.01$; 26–35 vs. 56–65, $p = 0.05$; Euclidean: 21–25 vs. 56–65, $p = 0.003$; 26–35 vs. 56–65, $p = 0.03$).

The above analyses separated participants into six age groups, which provided stable estimates of performance within each age group. To better understand the tendencies of age-related changes in local geometrical visual perception further, we treated age as a continuous variable and directly examined the relationship between performance and age. A Pearson's correlation coefficient between age and IE scores for each stimulus type was calculated. As shown in Figure 3, a statistically significant correlation between age and the IE score of local geometrical properties was obtained: (orientation, $r = 0.5$, $p < 0.001$; parallelism, $r = 0.5$, $p < 0.001$; collinearity, $r = 0.47$, $p < 0.001$; whereas there was no significant correlation between age and the IE score for global topological properties (two holes, $r = 0.06$, $p = 0.46$; one hole, $r = 0.02$, $p = 0.82$; presence/absence, $r = 0.005$, $p = 0.96$).

The results of the correlation analysis further suggest that local geometrical visual perception clearly deteriorate with aging, whereas global topological visual perception remains constant across the entire adult lifespan.

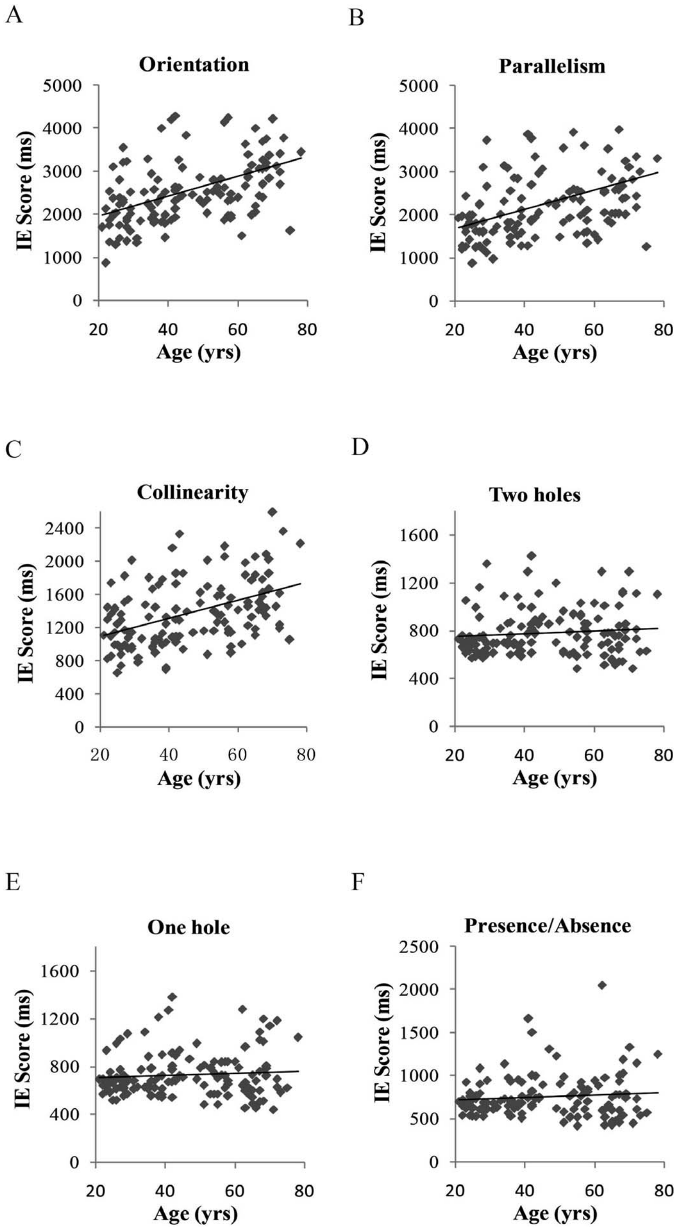

Figure 3. Relationship Results of Experiment 2. (A–F) Relationship of the mean IE scores of Euclidean (orientation), affine (parallelism), projective (collinearity), and topological (two holes, one hole, presence/absence) discrimination tasks with age.

Discussion

The data presented above, which was generated using the configural superiority effect paradigm, demonstrates a linear correlation between response times and the stratification of the geometric configuration; that is, the more complex the configuration is, the slower the response is. In particular, global topological perception (based on physical connectivity) occurred prior to the perception of other local geometrical properties, namely, projective, affine, and Euclidean. Experiment 1 directly compared effects due to aging on local and global geometric topological visual perception in a comparison of a young versus an old group. It was determined that compared with the young adults, the old adults showed an obvious perceptual deficit in local geometrical visual perception: Euclidean (orientation), affine (parallelism), and projective (collinearity). However, with respect to the global topological discrimination task, the performance of older adults was as good as that of younger adults. Experiment 2 further provided continuous-aging data from 21 to 78 years of age to investigate the tendencies of the aging process. The results indicate that there was a continuous age-related perceptual deficit in local geometrical perception. Experiment 2 provides further and more detailed evidence to indicate that for projective, affine, and Euclidean discrimination, the perceptual response was slower in the 56–65 years old group compared to that of younger groups. Moreover, by adding another kind of global topological property (presence vs. absence), Experiment 2 revealed a perceptual stability of global topological function against the aging process over the entire adult lifespan. The results of the present study demonstrate not only a good match between the stratification of geometries and reaction times, but also the speed of age-related perceptual deterioration.

However, recent studies by Norman and colleagues (Norman et al., 2017; Norman, Adkins & Pedersen, 2016; Norman et al., 2015; Norman et al., 2006) concerning age-related visual function that require judgment of Euclidean properties found that older adults can visually discriminate 3D solid object and can also evaluate distances in different directions in 3D situations just as well as younger adults or even more accurately than younger adults. At first glance, the results reported here appear to contradict this. We think there may at least two explanations for the discrepancy. First, Norman and colleagues measured accuracy, whereas the current study measured accuracy and RTs. It has been suggested that reaction time and accuracy may not always be equivalent measures of the underlying processes involved in visual recognition (Santee & Egeth, 1982). When performing a same analysis of the accuracy, we indeed found that there was no difference in the accuracy of projective, affine, and Euclidean perception discrimination task between different aged groups in Experiment 1 and Experiment 2 (see Results). Our results were consistent with Norman's studies. We are also in agreement that older people could discriminate the difference of Euclidean, affine, and projective properties as accurately as young people, yet we found they needed more time to achieve the same level of performance, which leads to an increase in RTs in Experiment 1 (see Results).

However, due to the near-ceiling performance in our study, further experiments are still needed to address this issue directly.

Second, note that our work was motivated by the global-first topological approach, which speaks to 2D topology and considers that the 2D topological properties are extracted as the starting point of the formation of an object representation, before 3D structures are constructed from 2D images (Chen, 2005; Zhou et al., 2010). In this sense, the concept of "global visual perception" and "local visual perception" in this study speaks to the visual perception of 2D topological, projective, affine, and Euclidean properties. The findings from Norman and colleagues' studies are very interesting and mainly based on a 3D shape or a distance discrimination in a complex scene presented on a computer screen where depth perception may be involved. Considering the complex relationship between 2D and stereoscopic depth perception, more studies are needed to clarify the age-related difference between two-dimensional and three-dimensional visual perception.

Many studies attempt to explain the mechanisms underlying age-related changes in visual perception. Until now, most of these studies have focused on the optical characteristics of the aging eye condition, such as reduced retinal illuminance, pupillary miosis, and increased lens density (Chylack et al., 1993; Loewenfeld, 1979; Spence, Kingstone, Shore, & Gazzaniga, 2001; Townsend & Ashby, 1983). Despite well-documented physical deficits in eye condition, some psychophysical studies have suggested that neural deterioration in visual pathways may also contribute to perceptual changes. For example, in humans, the ganglion cells in the retina are lost with aging (Curcio & Drucker, 1993; Loewenfeld, 1979; Pokorny, Smith, & Lutze, 1987). In primate studies, it was found that the neuronal responses to orientation and spatial contrast in the visual cortex are reduced in older monkeys (Curcio, Millican, Allen, & Kalina, 1993; Gao & Hollyfield, 1992). Bearing in mind these previous studies, it is easier to accept the age-related loss of local geometrical visual perception. However, an understanding of the neural bases of perceptual stability of global topological perception during aging remains unclear.

Functional magnetic resonance imaging (fMRI) studies investigating the neural correlates of global topological sensitivity found that the anterior temporal lobe is involved as a dedicated region (Wang et al., 2007; Zhou et al., 2010). However, an infant study showed that new-born human infants, two to three days after birth, have already manifested the ability to discriminate topological properties, such as holes (Turati, Simion, & Zanon, 2003). Furthermore, evidence from animal and insect studies indicates that different visual systems across species are sensitive to global topological patterns. For instance, in rodent species, mice, not considered to be "visual animals" due to their retinal degeneration and lack of infoldings in the cortex, are sensitive to figures that differ only in topological properties without any differences in local features (Zhu, Guo, Ma, & Ren, 2010). Surprisingly, bees, ancient evolutionary organisms without cortical systems and with less than 0.01% of the neurons present in the human brain, are also able to represent the general property of topological invariance (Chen, Zhang, & Srinivasan, 2003). Recent functional magnetic resonance imaging (fMRI) and TMS work in our lab (Meng et al., 2013) suggest that a rapid subcortical visual pathway is also involved in the coding of global topological information under poor visual conditions. According to Chen's theory and our present study, we suggested that global topological pattern recognition is a fundamental aspect of visual processing with multiple accessible sites and routes. Although available MRI studies in humans have reported an aging decline in the temporal lobe (Sullivan, Marsh, Mathalon, Lim, & Pfefferbaum, 1995; Ylikoski, Leskelä, Ylikoski, Salonen, & Mäntylä, 2010) and subcortical structures (thalamic and amygdala; Guttmann, Jolesz, Kikinis, Killiany, & Moss, 1998; Mu, Xie, Wen, Weng, & Shuyun, 1999; Seidman, Faraone, Goldstein, Goodman, & Kremen, 1996; Sullivan et al., 1995), we suggest that the multiple sites and routes could complement each other to facilitate global topological processing gaining priority to overcome the effect of aging-related loss in neural tissues and functions. However, further investigation is needed to clarify this issue.

Regarding how the processing of global topological information may alleviate the effects of aging, the present work is the first to provide direct evidence revealing differential aging effects on the visual perception of 2D local and global images. Particularly, local geometrical perception showed an obvious age-related decline, whereas global topological perception was immune to the aging process. These findings highlight the possibility that for human beings, global topology may be a stable and fundamental component by which visual systems represent and characterize objects.

Keywords: age, early vision, configural superiority effect, global topological visual perception, local geometrical visual perception

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References

Artal, P., Guirao, A., Berrio, E., Piers, P., & Norrby, S. (2003). Optical aberrations and the aging eye. *International Ophthalmology Clinics*, *43*, 63–77.

Atchley, P., & Anderson, G. J. (1998). The effect of age, retinal eccentricity, and speed on the detection of optic flow components. *Psychology and Aging*, *13*(2), 297–308.

Chen, L. (1982, November 12). Topological structure in visual perception. *Science*, *218*, 699–700.

Chen, L. (2005). The topological approach to perceptual organization. *Visual Cognition*, *12*, 553–637.

Chen, L., Zhang, S. W., & Srinivasan, M. V. (2003). Global perception in small brains: Topological pattern recognition in honeybees. *Proceedings of the National Academy of Sciences, USA*, *100*, 6884–6889.

Chylack, L. T., Jr., Wolfe, J. K., Singer, D. M., Leske, C., Bullimore, M. A., Bailey, I. L., . . . Wu, S. Y. (1993). The lens opacities classification system III. *Archives of Ophthalmology*, *111*, 831–836.

Curcio, C. A., & Drucker, D. N. (1993). Retinal ganglion cells in Alzheimer's disease and aging. *Annals of Neurology*, *33*, 248–257.

Curcio, C. A., Medeiros, N. E., & Millican, C. L. (1996). Photoreceptor loss in age related macular degeneration. *Investigative Ophthalmology & Visual Science*, *37*(7), 1236–1249.

Curcio, C. A., Millican, C. L., Allen, K. A., & Kalina, R. E. (1993). Aging of the human photoreceptor mosaic: Evidence for selective vulnerability of rods in central retina. *Investigative Ophthalmology & Visual Science*, *34*(12), 3278–3296.

Derefeldt, G., Lennerstrand, G., & Lundh, B. (1979). Age variations in normal human contrast sensitivity. *Acta Ophthalmologica*, *57*, 679–690.

Elliott, D. B., Whitaker, D., & MacVeigh, D. (1990). Neural contribution to spatiotemporal contrast sensitivity decline in healthy eyes. *Vision Research*, *30*, 541–547.

Elliott, S. L., Choi, S. S., Doble, N., Hardy, J. L., Evans, J. W., & Werner, J. S. (2009). Role of high-order aberrations in senescent changes in spatial vision. *Journal of Vision*, *9*(2):24, 1–16, https://doi.org/10.1167/9.2.24. [PubMed] [Article]

Eisner, A., Klein, M. L., Zilis, J. D., & Watkins, M. D. (1992). Visual function and the subsequent development of exudative age-related macular degeneration. *Investigative Ophthalmology & Visual Science*, *33*(11), 3091–3102.

Gao, H., & Hollyfield, J. G. (1992). Aging of the human retina: Differential loss of neurons and retina epithelial cells. *Investigative Ophthalmology & Visual Science*, *33*, 1–17.

Glasser, A., & Campbell, M. C. W. (1998). Presbyopia and the optical changes in the human crystalline lense with age. *Vision Research*, *38*, 209–229.

Guttmann, C. R. G., Jolesz, F. A., Kikinis, R., Killiany, R. J., & Moss, M. B. (1998). White matter changes with normal aging. *Neurology*, *50*(4), 972–978.

Huang, Y., He, L., Wang, W., Meng, Q., Zhou, T., & Chen, L. (2018). What determines the object-level visual masking: The bottom-up role of topological change. *Journal of Vision*, *18*(1):3, 1–14, https://doi.org/10.1167/18.1.3. [PubMed] [Article]

Huang, Y., Zhou, T., & Chen, L. (2011). The precedence of topological change over top-down attention in masked priming. *Journal of Vision* *11*(12):9, 1–10, https://doi.org/10.1167/11.12.9. [PubMed] [Article]

Jackson, G. R., Curcio, C. A., Sloan, K. R., & Owsley, C. (2004). Photoreceptor degeneration in aging and age-related maculopathy. In P. L. Penfold & J. M. Provis (Eds.), *Macular degeneration: Science and medicine in practice* (pp. 45–62). New York: Springer-Verlag Inc.

Jackson, G. R., & Edwards, J. G. (2008). A short-duration dark adaptation protocol for assessment of age-related maculopathy. *Journal of Ocular Biology, Diseases, and Informatics*, *1*, 7–11.

Kline, D. W. (1987). Ageing and the spatiotemporal discrimination performance of the visual system. *Eye*, *1*, 323–329.

Kline, D. W., & Schieber, F. (1985). Vision and aging. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (pp. 296–331). New York: Van Nostrand Reinhold Co.

Kline, D. W., Schieber, F., Abusamra, L. C., & Coyne, A. C. (1983). Age, the eye, and visual channels: Contrast sensitivity and response speed. *Journal of Gerontology*, *38*, 211–216.

Loewenfeld, I. E. (1979). Pupillary changes related to age. In H. S. Thompson (Ed.), *Topics in neuro-ophthalmology* (pp. 124–150). Baltimore, MD: Williams & Wilkins.

Medeiros, N. E., & Curcio, C. A. (2001). Preservation of ganglion cell layer neurons in age-related macular degeneration. *Investigative Ophthalmology & Visual Science*, *42*, 795–803.

Meng, Q. L., Huang, Y., Zhou, K., Cui, D., Ma, Y. Y., & Chen, L. (2013). Different neural processing of hole and no-hole stimuli in early stages of cortical and subcortical visual pathway. *Journal of Vision*, *13*(9): 1006, https://doi.org/10.1167/13.9.1006. [Abstract].

Mu, Q., Xie, J., Wen, Z., Weng, Y., & Shuyun, Z. (1999). A quantitative MR study of the hippocampal formation, the amygdala, and the temporal horn of the lateral ventricle in healthy subjects 40 to 90 years of age. *AJNR. American Journal of Neuroradiology*, *20*(2), 207–211.

Norman, J. F., Adkins, O. C., Dowell, C. J., Shain, L. M., Hoyng, S. C., & Kinnard, J. D. (2017). The visual perception of distance ratios outdoors. *Attention, Perception, & Psychophysics*, *79*, 1195–1203.

Norman, J. F., Adkins, O. C., & Pedersen, L. E. (2016). The visual perception of distance ratios in physical space. *Vision Research*, *123*, 1–7.

Norman, J. F., Adkins, O. C., Pedersen, L. E., Reyes, C. M., Wulff, R. A., & Tungate, A. (2015). The visual perception of exocentric distance in outdoor settings. *Vision Research*, *117*, 100–104.

Norman, J. F., Crabtree, C. E., Norman, H. F., Moncrief, B. K., Herrmann, M., & Kapley, N. (2006). Aging and the visual, haptic, and cross-modal perception of natural object shape. *Perception*, *35*, 1383–1395, http://dx.doi.org/10.1068/p5504.

Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, *23*, 689–699.

Pokorny, J., Smith, V. C., & Lutze, M. (1987). Aging of the human lens. *Applied Optics*, *26*(8), 1437–1440.

Pomerantz, J. R. (2003). Wholes, holes, and basic features in vision. *Trends in Cognitive Sciences*, *7*, 471–473.

Raymond, B., & Marc, B. (2011). Combining speed and accuracy in cognitive psychology: Is the Inverse Efficiency Score (IES) a better dependent variable than the mean Reaction Time (RT) and the Percentage of Errors (PE)? *Psychologica Belgica*, *51*(1), 5–13.

Ross, J. E., Clarke, D. D., & Bron, A. J. (1985). Effect of age on contrast sensitivity function: Uniocular and binocular findings. *British Journal of Ophthalmology*, *69*, 51–56.

Said, F. S., & Weale, R. A. (1959). The variation with age of the spectral transmissivity of the living human crystalline lens. *Gerontologia*, *3*, 213–231.

Santee, J. L., & Egeth, H. E. (1982). Do reaction time and accuracy measure the same aspects of letter recognition? *Journal of Experimental Psychology: Human Perception and Performance*, *8*(4), 489–501.

Seidman, L. J., Faraone, S. V., Goldstein, J. M., Goodman, J. M., & Kremen, W. S. (1996). Thalamic and amygdala–hippocampal volume reductions in first-degree relatives of patients with schizophrenia: An MRI-based morphometric analysis. *Biological Psychiatry*, *46*(7), 941–954.

Spence, C., Kingstone, A., Shore, D. I., & Gazzaniga, M. S. (2001). Representation of visuo tactile space in the split brain, *Psychological Science*, *12*, 90–93.

Starita, C., Hussain, A. A., Pagliarini, S., & Marshall, J. (1996). Hydrodynamics of aging Burch's membrane: Implications for macular disease. *Experimental Eye Research*, *62*, 565–572.

Sullivan, E. V., Marsh, L., Mathalon, D. H., Lim, K. O., & Pfefferbaum, A. (1995). Age-related decline in MRI volumes of temporal lobe gray matter but not hippocampus. *Neurobiology of Aging*, *16*, 591–606.

Townsend, J. T., & Ashby, F. G. (1983). *Stochastic modelling of elementary psychological processes*. New York, NY: Cambridge University Press.

Turati, C., Simion, F., & Zanon, L. (2003). Newborns' perceptual categorization for closed and open geometric forms. *Infancy*, *4*, 309–325.

Sunness, J. S., Rubin, G. S., Broman, A., Tulunay-Keesey, U., VerHoeve, J. N., & Terkla-McGrane, C. (1988). Threshold and suprathreshold spatiotemporal response throughout adulthood. *Journal of the Optical Society of America*, *A5*, 2191–2200.

Vinding, T. (1990). Occurrence of drusen, pigmentary changes and exudative changes in the macula with reference to age-related macular degeneration: An epidemiological study of 1000 aged individuals. *Acta Ophthalmologica*, *68*, 410–414.

Wang, B., Zhou, T. G., Zhuo, Y., & Chen, L. (2007). Global topological dominance in the left hemisphere. *Proceedings of the National Academy of Sciences, USA*, *104*, 21014–21019.

Weale, R. A. (1961). Retinal illumination and age. *Transactions of the Illuminating Engineering Society*, *26*(2), 95–100.

Ylikoski, A., Leskelä, M., Ylikoski, R., Salonen, O., & Mäntylä, R. (2010). Hippocampal and temporal lobe atrophy and age-related decline in memory. *Acta Neurologica Scandinavica*, *101*(4), 273–278.

Zhou, K., Luo, H., Zhou, T. G., Zhuo, Y., & Chen, L. (2010). Topological change disturbs object continuity in attentive tracking. *Proceedings of the National Academy of Sciences, USA*, *50*, 21920–21924.

Zhu, J., Guo, X. Y., Ma, Y., & Ren, F. (2010). Different topological properties pattern recognition in Mice. *Progress in Biochemistry and Biophysics*, *37*(6), 613–617.

Zhuo, Y., Zhou, T. G., Rao, H. Y., Wang, J. J., Meng, M., Chen, M., … Chen, L. (2003, January 17) Contributions of the visual ventral pathway to long-range apparent motion. *Science*, *299*, 417–420.