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A window on the normal development of sensitivity to global form in Glass patterns

Terri L Lewis¶§, Dave Ellemberg#, Daphne Maurer¶, Melanie Dirks, Fran Wilkinson‡, Hugh R Wilson‡
Department of Psychology, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4K1, Canada; e-mail: LewisTL@mcmaster.ca
¶ also at Department of Ophthalmology, The Hospital for Sick Children, Toronto, Canada
§ also at Department of Ophthalmology and Vision Sciences, University of Toronto, Toronto, Canada
# also at Department of Ophthalmology, Vision Research Unit, McGill University, 687 Pine Avenue West, Montréal, Québec H3A 1A1, Canada
‡ Department of Psychology, York University, 4700 Keele Street, Toronto, Ontario M3J 1P3, Canada
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Abstract. We studied the development of sensitivity to global form in 6-year-olds, 9-year-olds, and adults ($n = 24$ in each group) using Glass patterns with varying ratios of paired signal dots to noise dots. The developmental pattern was similar whether the global structure within the Glass patterns was concentric or parallel. Thresholds were equally immature for both types of pattern at 6 years of age (about twice the adult value) but were adult-like at 9 years of age. Together, the results indicate that the cortical structures involved in the processing of global form achieve functional maturity between 6 and 9 years of age. During middle childhood, the mechanisms mediating sensitivity to concentric structure develop at the same rate as those mediating sensitivity to parallel structure.

1 Introduction

Even newborn babies are capable of perceiving the global structure of a form, an ability that requires the integration of local elements into a larger form. Specifically, after being habituated to an array of local elements consisting of horizontal rows of small black squares alternating with horizontal rows of small white squares, newborns treat vertical black-and-white stripes as novel and horizontal black-and-white stripes as familiar (Farroni et al 2000). Presumably, the newborns integrated the rows of elements with similar luminance into the global pattern of horizontal stripes, as described by the Gestalt principle of luminance similarity. By 3 – 4 months of age, infants demonstrate sensitivity to various aspects of global structure, such as the amount of symmetry in a pattern (Humphrey and Humphrey 1989), the global configuration of dot arrays (Humphrey et al 1986; Quinn 2000), and the global configuration of oriented line segments (Curran et al 2000; Humphrey et al 1988). For example, 4-month-olds habituated to a concentric array of line segments show a novelty effect both when the same line segments are organised randomly and when they are organised in a radial pattern (Humphrey et al 1988). Similarly, when short line segments oriented in a concentric array are presented to the left or right of centre in a background of randomly oriented line segments, 12-week-olds (but not 10-week-olds) look longer at the side with the concentric array (Curran et al 2000).

Although young infants can sometimes perceive the structure in global form, little is known about the development of sensitivity to it. In one of the few studies investigating thresholds for detecting global form during normal development, Gunn and colleagues (2002) showed subjects a concentric array of line segments (signal) in a background of randomly oriented line segments. Over trials, the proportion of signal elements in the concentric array was varied to estimate the minimum percentage of signal necessary to detect the location of the concentric pattern. The authors concluded that sensitivity to concentric global form was mature in children aged 6 to 7 years but not in 5-year-olds (1.3 times worse than adults).

Thresholds for the perception of global form are thought to provide psychophysical estimates of global processing by pattern-sensitive mechanisms in the extrastriate visual cortex. Specifically, investigators have hypothesised that local elements can be detected by simple and complex cells in the primary visual cortex. The output of these cells is then integrated to create the perception of global form (reviewed in Wilson 1999). Computational models of form perception (Wilson 1999; Wilson and Wilkinson 1998), supported by psychophysical (Glass and Switkes 1976; Wilson et al 1997), physiological (Gallant et al 1993, 1996; Pasupathy and Connor 1999), neuropsychological (Gallant et al 2000), ERP (Allison et al 1999), and fMRI (Wilkinson et al 2000) data are consistent with the hypothesis that extrastriate area V4v in the ventral visual pathway plays a key role in the perception of global form, particularly in the perception of concentric global form. For example, single-cell recordings of the monkey have identified a type of cell in area V4v responsive primarily to concentric structure (Gallant et al 1993, 1996; Pasupathy and Connor 1999), whereas such cells are very rare in area V2, the area preceding V4 in the ventral visual pathway (Kobatake and Tanaka 1994). Although the specific involvement of area V4v remains somewhat controversial (see, for example, Braddick et al 2000), there is general consensus that, in humans, the processing of global form occurs in extrastriate areas distinct from those that process the perception of global motion.

Several pieces of evidence suggest that global forms with concentric or radial structure (non-Cartesian patterns) are processed differently than global forms with parallel structure (Cartesian patterns). Very young kittens can learn to discriminate a concentric from a radial pattern and horizontal stripes from vertical ones, even when local cues to form are eliminated; however, kittens require nearly twice the number of trials to reach criterion for parallel patterns than for the concentric/radial ones (Dodwell et al 1983; Wilkinson and Dodwell 1980). Moreover, under most testing conditions, human adults require more signal in a background of noise to detect parallel than concentric structure in global form (Dakin 1997, 1999; Wilson and Wilkinson 1998; Wilson et al 1997), although under some conditions these differences disappear with sufficient practice (Dakin and Bex 2002; Wilson and Wilkinson 2003). Finally, single-cell recordings in monkeys indicate that, although most cells in extrastriate area V4v transmit significant amounts of information about both concentric and parallel structure, their average response is 25%–30% lower for parallel than for concentric stimuli (Gallant et al 1996).

Glass (1969) patterns are ideal stimuli for studying sensitivity to concentric and parallel structure in global form (eg Dakin 1997; Gallant et al 2000; Movshon et al 2003; Wilson and Wilkinson 1998; Wilson et al 1997). Glass (1969) noted that when a pattern of random dots is superimposed over an identical pattern and rotated a critical amount about the central axis, a compelling perception of concentric swirls arises. Similarly, when the superimposed pattern is, instead, displaced vertically, the perception of parallel stripes arises. These patterns, now known as concentric and parallel Glass patterns, respectively, can be used to assess sensitivity to global form by varying the ratio of paired signal dots to noise dots until the subject can no longer discriminate accurately between the signal pattern and a pattern comprised solely of noise dots.

Previous studies with Glass patterns indicate that differential responding to concentric versus parallel structure may occur because the two types of pattern are processed by different underlying neural mechanisms. Based on their measurements of differences in the extent of global pooling for concentric versus parallel structure in Glass patterns and on their calculations of the receptive field characteristics necessary to process each type of pattern, Wilson et al (1997) and Wilson and Wilkinson (1998) proposed that global forms with concentric structure are processed in extrastriate area V4v whereas global forms with parallel structure may be processed by complex cells in areas V1/V2 like those described by Movshon et al (1978). However, recent studies by Movshon and colleagues demonstrate that, in monkeys, the processing of parallel structure in Glass patterns occurs beyond area V2 (Movshon et al 2003; Smith et al 2002). Nonetheless, concentric and parallel structure may still be processed by different underlying neural mechanisms in the extrastriate ventral stream beyond area V2. An alternative model suggests that there may be a common mechanism underlying processing of global forms whether the structure is concentric or parallel (Dakin 1997, 1999).

The purpose of the present study was to assess the functional development of the extrastriate areas involved in the perception of global form by measuring changes during middle childhood in sensitivity to structure in Glass patterns. We included both concentric and parallel Glass patterns because a finding of different rates of development for the two types of pattern would support the hypothesis that the two types of global form are processed by different underlying neural mechanisms or even by different cortical areas.

2 Methods

2.1 *Subjects*

Subjects were twenty-four 6-year-olds (±3 months), twenty-four 9-year-olds (±3 months), and twenty-four adults (range, 17 – 29 years; mean, 19.4 years). All subjects had no history of eye problems and met our criteria on a visual screening exam. Specifically, 9-year-olds and adults had a linear letter acuity on the Lighthouse Distance Visual Acuity Test chart of at least 20/20 in each eye without optical correction, worse acuity with a +3 dioptre add (to rule out hypermetropia greater than 3 dioptres), fusion at near on the Worth four-dot test, and stereoacuity of at least 40 s of arc on the Titmus test. The criteria for 6-year-olds were the same except we tested acuity with the Good-Lite Crowding cards.

2.2 *Apparatus and stimuli*

The stimuli were created in Matlab™ and generated by an Apple Macintosh G3 computer on a Sony Trinitron Multiscan 200 GS monitor. Frame rate was 75 Hz and screen resolution was 1024×768 pixels. The stimuli, when viewed from 57 cm, were contained within a 12 deg circle that was centred on the monitor. They were composed of white dots (mean luminance, 81.6 cd m^{-2}) on a grey background (mean luminance, 35.8 cd m^{-2}). 'Signal patterns' consisted of concentric or parallel Glass patterns, constructed in a manner similar to that described by Wilson and Wilkinson (1998). Briefly, for concentric Glass patterns, pairs of dots were placed at random within the pattern, but the orientation of the pair was always tangent to a circle centred on the pattern. The pattern was made up of square 'dots' with 1.8 min of arc sides, a density of 6%, and a separation of 16.2 min of arc between members of a pair. Under these conditions, the mean dot spacing overall was 7.9 min of arc, less than half the spacing between members of a pair. This arrangement ensured that the perception of global structure was not based on local cues of dot spacing. The construction of parallel Glass patterns was identical, except that the orientation of the signal pairs was always vertical. Figure 1 illustrates an example of concentric and parallel Glass patterns with 100% signal.

Signal patterns were degraded to varying degrees by replacing a percentage of the signal-dot pairs with an equal number of randomly spaced noise dots that were the same size and shape as the signal dots. To measure thresholds for detecting global structure in Glass patterns, subjects discriminated signal patterns from noise patterns. Noise patterns contained the same percentages of dot pairs as the signal patterns, except that each noise dot pair was plotted at a random orientation, thus providing no

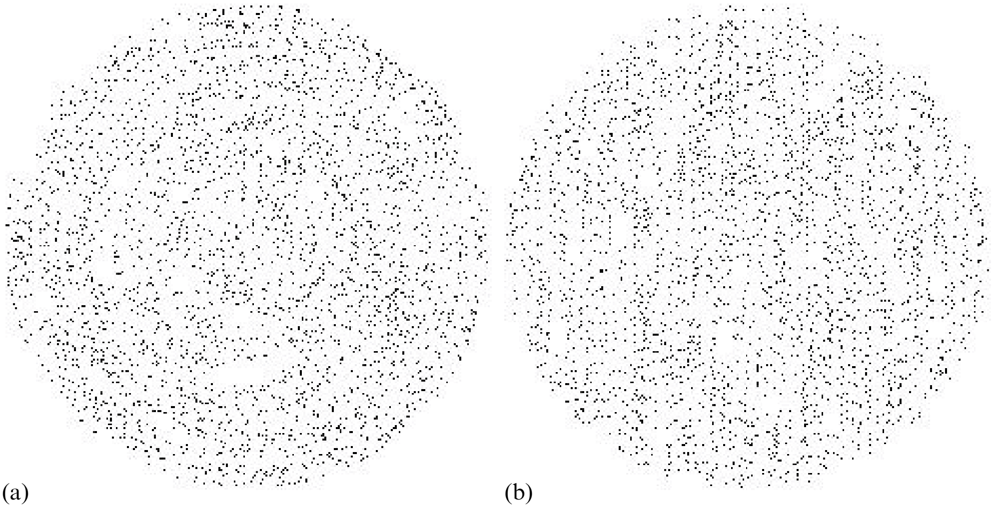

Figure 1. Examples of concentric (a) and parallel (b) structure in Glass patterns with 100% signal. For concentric Glass patterns, the orientation of dot pairs was always tangent to a circle centred on the pattern. The construction of parallel Glass patterns was identical except that the orientation of the dot pairs was always vertical. For clarity, the patterns are illustrated with black dots on a white ground but the actual stimuli contained white dots on a grey ground.

global shape cues. The remaining dots in each noise pattern were randomly positioned. Thus, noise patterns contained the same percentages of dot pairs and random single dots as the signal patterns but lacked global structure (Wilson and Wilkinson 1998; Wilson et al 1997). Accordingly, only global structure could be used as a cue for discrimination.

2.3 *Procedure*

The procedures were explained and written consent was obtained from the parents of the children and from the adults who participated. Nine-year-olds also gave informed assent. The experimental protocol was approved by the Committee on the Ethics of Research on Human Subjects, McMaster University, and by the Research Ethics Board of The Hospital for Sick Children.

Subjects were tested binocularly in a room illuminated only by the computer monitor and were adapted to the lighting conditions prior to the test. They sat 57 cm from the computer screen with their chin in a chin-rest. Parents of children sat in the testing room out of their child's sight and were asked to remain silent during testing.

The experimenter began by instructing the subject to fixate the centre of the monitor and, for concentric stimuli, said: "You are going to see a circle filled with dots and it is your job to tell me if the dots look all messy (experimenter moves his/her finger in random directions in front of the computer screen) or if you see swirls (experimenter draws imaginary circles in front of the computer screen)". The instructions for the parallel stimuli were the same except that subjects were asked to say if they saw messy dots or lines. The experimenter pressed a key to begin a trial and each stimulus remained on the screen for 1500 ms. The experimenter watched the subject to ensure that he/she maintained central fixation, provided regular reminders to do so, and began a trial only when the subject was looking in the middle of the screen. The procedure began with demonstration trials and a practice run.

2.3.1 *Demonstration trials.* The demonstration consisted of four trials, each lasting 1500 ms, one with 100% signal and one with 75% signal, each alternating with a noise pattern. The experimenter taught the subject to discriminate noise from signal trials providing the correct answer followed by a verbal explanation after each demonstration trial and, for signal trials, tracing the pattern with his/her finger.

2.3.2 *Criterion trials.* The purpose of criterion trials was to verify that the subject understood the task. The set consisted of eight noise trials and eight signal trials (60% signal for concentric patterns and 100% signal for parallel patterns), presented in a random order. The subject's task on each trial was to say whether or not the pattern contained swirls (or lines). To pass criterion, subjects had to get four in a row correct with feedback. All subjects passed criterion.

2.3.3 *Practice run.* For the practice run and the subsequent threshold measurements, we used a two-alternative temporal forced-choice procedure combined with the method of constant stimuli. The two intervals in a trial each lasted 1500 ms with an inter-stimulus interval of 500 ms. To help keep the subject alert, the experimenter often said: "Are the swirls (or lines) in number one (timed to coincide with the presentation of the first interval) or in number two (timed to coincide with the presentation of the second interval)?" After each trial, the experimenter coded the subject's response on a keypad. A practice run consisted of eight trials during which four signal values (60%, 40%, 25%, and 10% for concentric patterns; 100%, 75%, 50%, and 10% for parallel patterns) were each presented twice in a random order. Across trials, the signal appeared randomly in interval 1 or 2. The experimenter was aware of the stimulus presented during each interval and, if the subject began making mistakes on 'easy' trials, provided feedback. One purpose of this practice run was to let subjects know what to expect when the signal/noise ratio was near threshold. The particular signal values chosen for concentric versus parallel patterns were based on pilot work.

2.3.4 *Test of thresholds.* The procedure for measuring each threshold was identical to that for the practice run except (1) signal values were modified if necessary to bracket the threshold obtained on the practice run, (2) the four signal values were each presented 20 times in a random order, and (3) the experimenter was unaware of the stimulus presented during each interval and provided encouragement but no feedback. The percentage of correct responses was plotted as a function of signal value and the data were fit by a Quick (1974) or Weibull (1951) function by using a maximum-likelihood procedure. Thresholds were defined as the percent signal necessary to obtain 75% correct responses.

Each subject completed two tests: one for patterns with concentric structure and one for patterns with parallel structure. Half the subjects in each group first completed a test with the concentric structure, and half with the parallel structure.

2.4 *Data analyses*

To assess developmental changes in sensitivity to global structure, we conducted a 2-way mixed analysis of variance (ANOVA) with a between-subject variable of group with three levels (6-year-olds, 9-year-olds, adults) and a within-subject variable of pattern with two levels (concentric, parallel). The between-subjects factor was further analysed by means of Fisher's PLSD test (Howell 2002).

3 Results

Figure 2 shows the minimum percentage of paired signal dots necessary to detect the overall parallel structure (squares) and overall concentric structure (circles) in Glass patterns for 6-year-olds, 9-year-olds, and adults. There was a significant difference in performance amongst the three groups (main effect of group: $F_{2,69} = 15.82$, $p < 0.0001$). Thresholds of 6-year-olds (parallel mean, 52.8%; concentric mean, 29.3%) were significantly higher than those of 9-year-olds (parallel mean, 27.6%; concentric mean, 16.4%) and those of adults (parallel mean, 30.0%; concentric mean, 12.3%) (ps < 0.0001).

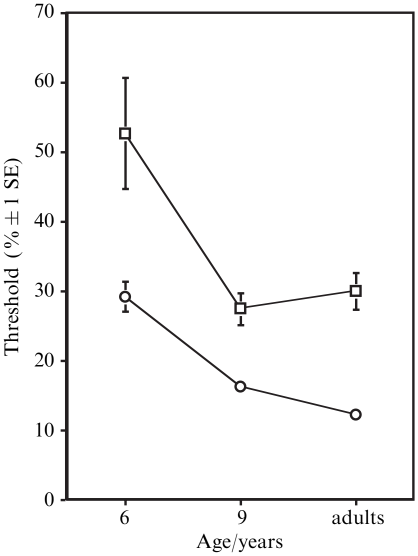

Figure 2. Mean threshold representing the minimum percentage signal necessary to perceive the global structure in Glass patterns accurately 75% of the time. Data are for 6-year-olds, 9-year-olds, and adults. Squares represent the results for patterns with parallel structure and circles represent the results for patterns with concentric structure.

However, thresholds of 9-year-olds were no different than those of adults ($p > 0.80$). For all three groups, thresholds were significantly worse for patterns with parallel structure than for patterns with concentric structure (main effect of pattern: $F_{1,69} = 39.94$, $p < 0.0001$), but the size of this difference did not vary with age (nonsignificant interaction between group and pattern: $F_{2,69} = 1.65$, $p > 0.10$).(1)

4 Discussion

The thresholds that we obtained from adults are similar to those obtained from previous studies with similar stimuli. In the present study, adults' signal thresholds were 12% for concentric patterns and 30% for parallel patterns. With similar stimuli, others have obtained mean thresholds in adults ranging from 12% to 18% for concentric patterns and ranging from 27% to 56% for parallel patterns (Dakin and Bex 2002; Gunn et al 2002; Wilson and Wilkinson 1998; Wilson et al 1997). Moreover, our finding that adults performed 2.5 times worse for parallel than for concentric structure is within the range of values reported in other studies that used stimuli similar to ours to make the comparison (range across studies = 1.5 – 4.7 times worse for parallel than concentric structure—Dakin and Bex 2002; Wilson and Wilkinson 1998; Wilson et al 1997). The similarity in findings is especially convincing because the samples ranged from three psychophysically practiced observers (Wilson et al 1997), to twenty-four naïve adults (this study) to sixty-five naïve adults (Gunn et al 2002).

The results from children suggest that sensitivity to global form is immature at 6 years of age: the thresholds of 6-year-olds were only about half as good as those of adults.

(1) To verify that unequal variance in the results for parallel versus concentric patterns did not mask a significant interaction, we computed a difference score for each subject (threshold for parallel pattern minus threshold for concentric pattern), and then did a one-way between-subjects ANOVA on those difference scores. The ANOVA was not significant, indicating that the differences in performance between parallel and concentric patterns did not change with age, and that sensitivity to the two types of pattern did, in fact, mature at the same rate. This was true both when we used the usual degrees of freedom (df $= 2, 69$) and when we used the conservative F-test (df $= 1, 23$) to compensate for unequal variance across the difference scores (Box 1954). Similarly, a conservative F-test (Box 1954) on the original ANOVA confirmed the original results and indicated that unequal variance in the between-subjects factor did not affect the conclusions about changes with age in sensitivity to parallel versus concentric patterns.

The results also suggest that sensitivity reaches adult levels sometime between 6 and 9 years of age. The relatively poor performance in 6-year-olds cannot be attributed to an inability to see the dots making up the pattern. Contrast sensitivity is nearly adult-like at 6 years of age (Ellemberg et al 1999) and all 6-year-olds could see the global structure, provided that the percentage of signal dots was sufficiently high.

Nonvisual factors, such as differences between 6-year-olds and 9-year-olds in attention and criterion, may have contributed to the age differences but are unlikely to account fully for the differences in thresholds. By the age of 6 years, children perform as well as adults on some psychophysical tasks that have performance demands like those in the present study, namely tasks that use two-alternative forced-choice procedures to measure thresholds. For example, studies of sensitivity to the direction of local motion indicate that thresholds of 5-year-olds are nearly adult-like for first-order (luminance-defined) stripes moving at 1.5 or 6 deg s^{-1} and for second-order (contrast-defined) stripes moving at 1.5 deg s^{-1} (Ellemberg et al 2000, 2003). Similarly, sensitivity to the direction of global motion is mature by 6 years of age when children are tested with random-dot kinematograms moving at a speed of 18 deg s^{-1}: like adults, they need only about 8% of dots to move coherently in order to identify accurately their direction of motion (Ellemberg et al 2002). However, at least under some conditions, sensitivity to the direction of global motion is immature at 5 years of age, and the degree of immaturity varies with speed, displacement, and whether the direction of motion is defined by first-order or second-order cues (Ellemberg et al 2001, submitted). This pattern of results indicates that two-alternative forced-choice procedures can be used successfully by the age of 5 years to detect differential rates of development for visual capabilities mediated by different neural mechanisms. Additional evidence that nonvisual factors do not account fully for the poorer performance of the 6-year-olds in the present study is the finding that, at all ages, thresholds were twice as good for concentric structure than they were for parallel structure, a pattern that is likely to be caused by similar neural factors at all ages. Overall, our results suggest that the neural mechanisms involved in perception of global form are still immature at 6 years of age.

Our findings of immature sensitivity at 6 years of age are compatible with those from the only other study measuring sensitivity to concentric global structure in middle childhood (Gunn et al 2002). Six-year-olds in the present study ranged in age from 5.75 to 6.25 years and thus overlapped in age both with the lower end of Gunn's group of 6-year-olds and 7-year-olds who had adult-like thresholds (a group of sixty children aged 6.0 – 7.99 years) and the higher end of Gunn's 5-year-olds who had immature thresholds (a group of ninety-three children ranging in age from 5.3 – 5.99 years). Thus, had Gunn et al tested narrower age ranges, they may have found that sensitivity to global form with concentric structure is still immature at 6 years of age. To our knowledge, there has been no previous study of sensitivity to global form with parallel structure during middle childhood.

We found that sensitivity to global structure in Glass patterns was, on average, 2.1 times worse in 6-year-olds than in adults. This immaturity is greater than that for grating acuity or spatial contrast sensitivity. Specifically, 6-year-olds have adult-like grating acuity, and thresholds for contrast sensitivity are, on average, only 1.4 times worse than those of adults (Ellemberg et al 1999). This comparison suggests that sensitivity to global form, which is likely mediated primarily by cells in the extrastriate ventral stream, matures more slowly than spatial contrast sensitivity and acuity, nonmotion tasks that are likely mediated primarily by lower cortical or precortical areas (reviewed in Ellemberg et al 1999). This pattern is consistent with anatomical evidence from humans that extrastriate cortex matures more slowly than striate cortex (Conel 1939, 1951, 1955).

However, the age at which various ventral stream tasks become adult-like seems to vary with the particular task. For example, in the present study, we found adult-like performance beginning somewhere between 6 and 9 years of age for sensitivity to global form. Other researchers using different approaches and/or measuring different ventral stream capabilities have reported the onset of adult-like performance beginning at ages ranging from 2.5 years (Maurer et al 1989) to after 10 years (Kovács 2000; Mondloch et al 2002, 2003). Specifically, Maurer et al (1989) tested the perception of global form by having preschoolers match exemplars to one of four test shapes (triangle, circle, cross, and 'U'). Children as young as 30 months old (the youngest age tested) made virtually no errors even when the exemplars differed from the test shapes in size, luminance, contour, and/or the presence of masking lines. Conversely, even 14-year-olds are not as sensitive as adults when asked to report whether two faces are the same or different on the basis of subtle differences in the spacing of facial features, and when asked to find a continuous path of oriented Gabor patterns embedded in noise consisting of randomly oriented Gabors (Kovács 2000; Mondloch et al 2003).

Our findings suggest that, under the present testing conditions, sensitivity to concentric structure in global form matures at the same rate as sensitivity to parallel structure in global form. Both adults and 6-year-olds were less sensitive to parallel than to concentric structure, but 6-year-olds were equally immature for the two types of pattern. Similarly, young monkeys are less sensitive to parallel than to concentric structure in Glass patterns but are equally immature for the two types of pattern (Kiorpes 2003). Findings of equal immaturity cannot resolve ongoing debates about whether the perception of these two types of pattern is mediated by one underlying mechanism or by different underlying mechanisms that happen to mature at the same rate (cf Dakin and Bex 2003; Wilson and Wilkinson 2003). Nonetheless it should be stressed that concentric and parallel Glass patterns have locally similar structure (tangents to concentric circles are locally parallel), so lower thresholds for concentric patterns must reflect some form of global pooling across orientations (Wilson et al 1997).

5 Conclusions

Sensitivity to concentric and parallel structure in Glass patterns is immature in 6-year-olds and adult-like by 9 years of age, at least under the present testing conditions. Our findings that sensitivity in 6-year-olds is equally immature for the two types of pattern indicate that, during middle childhood, the mechanisms mediating sensitivity to concentric structure develop at the same rate as those mediating sensitivity to parallel structure. Further research is necessary to determine whether the perception of these two types of pattern is mediated by the same underlying mechanism or by different mechanisms that mature at the same rate.

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