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## The maturation of global motion perception depends on the spatial and temporal offsets of the stimulus

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### ABSTRACT

The typical development of motion perception is commonly assessed with tests of global motion integration using random dot kinematograms. There are discrepancies, however, with respect to when typically-developing children reach adult-like performance on this task, ranging from as early as 3 years to as late as 12 years. To address these discrepancies, the current study measured the effect of frame duration ( $\Delta t$ ) and signal dot spatial offset ( $\Delta x$ ) on motion coherence thresholds in adults and children. Two  $\Delta t$  values were used in combination with seven  $\Delta x$  values, for a range of speeds (0.3–38 deg/s). Developmental comparisons showed that for the longer  $\Delta t$ , children performed as well as adults for larger  $\Delta x$ , and were immature for smaller  $\Delta x$ . When parameters were expressed as speed, there was a range of intermediate speeds (4–12 deg/s) for which maturity was dependent on the values of  $\Delta x$  and  $\Delta t$  tested. These results resolve previous discrepancies by showing that motion sensitivity to a given speed may be mature, or not, depending on the underlying spatial and temporal properties of the motion stimulus.

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### 1. Introduction

The random dot kinematogram (RDK) is a commonly-used stimulus for assessing global motion perception. This stimulus has been used in clinical studies that compare the performance of patient populations (e.g., autism, [Milne et al., 2002](#); preterm children, [Taylor et al., 2009](#); dementia, [Silverman et al., 1994](#)) to healthy age-matched controls, and in cross-sectional studies that compare performance of aging populations to healthy young adult controls (e.g., [Snowden & Kavanagh, 2006](#)). This stimulus is also used to track the maturational trajectory of global motion perception in typically-developing children. However, there are discrepancies with respect to the age at which global motion perception matures to adult levels. Resolving these discrepancies was the main purpose of this study.

Estimates of the age at which global motion direction discrimination can be considered adult-like range from as young as 3 years to as old as 12. [Parrish et al. \(2005\)](#) compared coherence thresholds in children aged 3–12 and adults, and found no significant differences between thresholds, indicating global motion perception matures before age 3. Consistent with this, in clinical studies that included control groups of children and adults, no difference between control groups of 6-year-old children and adults were found

by [Elleberg et al. \(2002\)](#), or [Reiss, Hoffman, and Landau \(2005\)](#) on a motion detection task. In contrast, [Narasimhan and Giaschi \(2012\)](#) found that 5- to 6-year-old children had immature global motion perception, and a study by [Hadad, Maurer, and Lewis \(2011\)](#) testing children aged 6–14 found that maturation did not occur until age 12. Studies using random Gabor kinematograms, which are similar to RDKs but with Gabor patches rather than dots, have also found significant differences in global motion perception between 5-year-olds and adults ([Elleberg et al., 2004, 2010](#)).

Because each research group tends to create its own stimulus, it is likely that different stimulus parameters are driving performance differences in children and adults. However, the relationship between stimulus parameters and maturation is not obvious, from a simple review of the literature. For example, [Parrish et al. \(2005\)](#) and [Elleberg et al. \(2002\)](#) used up/down direction discrimination and found early maturation, but so did [Hadad, Maurer, and Lewis \(2011\)](#), who found quite late maturation. Both [Reiss, Hoffman, and Landau \(2005\)](#) and [Narasimhan and Giaschi \(2012\)](#) used left/right directions, and also came to different conclusions about 5- to 6-year-olds. Studies also differ in the type of noise algorithm used (direction noise: [Elleberg et al., 2002](#); [Hadad, Maurer, & Lewis, 2011](#); walk noise: [Narasimhan & Giaschi, 2012](#); [Parrish et al., 2005](#); white noise: [Reiss, Hoffman, & Landau, 2005](#)), and in the dot size and density used (small dots, dense stimulus: [Parrish et al., 2005](#); small dots, varying densities: [Narasimhan & Giaschi, 2012](#); large dots, sparse stimulus: [Elleberg et al., 2002](#); [Hadad, Maurer, & Lewis, 2011](#); [Reiss, Hoffman, &](#)

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Landau, 2005), but these properties do not identify which studies found early or late maturation. Studies used a range of stimulus durations, but studies using short (400 ms; Narasimhan & Giaschi, 2012) and long (2000 ms; Hadad, Maurer, & Lewis, 2011) durations came to similar conclusions about development.

The studies also overlap in the speeds they tested, ranging from 1 to 18 deg/s. Mature performance was found for 1.2 deg/s (Parrish et al., 2005), 2.5 deg/s (Reiss, Hoffman, & Landau, 2005), and 18 deg/s (Elleberg et al., 2002); and immature performance was found for 1 and 4 deg/s (Narasimhan & Giaschi, 2012), and 4 and 18 deg/s (Hadad, Maurer, & Lewis, 2011). However, there is evidence to suggest that the underlying spatial and temporal parameters used to create a speed matter more than simply their ratio (e.g., Arena, Hutchison, & Shimozaki, 2012; Elleberg et al., 2010; Kiorpes & Movshon, 2004; reviewed below). This may account for some conflicting conclusions on when global motion perception is adult-like.

Studies of preschool-aged children indicate sensitivity to fast motion matures earlier in life than sensitivity to slow motion. For example, Narasimhan and Giaschi (2012) found global motion direction discrimination thresholds in 5-year-olds were more immature at a speed of 1 deg/s than at 4 deg/s. Similarly, using random Gabor kinematograms, Elleberg et al. (2004) found children at this age were very immature at stimuli with speeds of 1.5 deg/s, and less so at 6 and 9 deg/s. Speed discrimination thresholds in 5-year-old children are also immature, but more so for reference speeds of 1.5 deg/s than for 6 deg/s (Ahmed et al., 2005). Children do not show adult-like thresholds in speed discrimination tasks until age 11 for reference speeds of 6 deg/s, and thresholds for speeds of 1.5 deg/s are still immature at this age (Manning, Aagten-Murphy, & Pellicano, 2012). In motion-defined form tasks, children aged 4–6 show adult-like coherence thresholds for stimuli moving at 5 deg/s, but are immature at 0.9 deg/s and even more so at 0.1 deg/s (Hayward et al., 2011). Some early developmental disorders have been shown to disrupt performance on motion tasks at slow speeds only, indicating a protracted sensitive period for damage. For example, Hayward et al. found that children with amblyopia had elevated thresholds for the motion-defined form task in the affected and unaffected eyes at 0.1 deg/s, but not at 0.9 or 5 deg/s, and Edwards et al. (2004) found elevated global motion direction discrimination thresholds in children with dyslexia for speeds of 0.24 and 1.2 deg/s, but not 7.3 deg/s.

The speed of a motion stimulus is calculated as the ratio  $\Delta x/\Delta t$ , where  $\Delta x$  represents the spatial offset of signal dots in an RDK, and  $\Delta t$  represents the temporal interval between subsequent animation frames. There is evidence to suggest that a measure of speed alone may not be the most informative indicator of coherence thresholds. In three direction-discrimination experiments with adults, Arena, Hutchison, and Shimozaki (2012) held  $\Delta x$ ,  $\Delta t$ , or speed constant while varying the other two parameters. When  $\Delta t$  was held constant at 107 ms and  $\Delta x$  was varied from 4 to 64 arcmin, they found thresholds were increased for spatial offsets greater than about 18 arcmin. When  $\Delta x$  was held constant at 37.5 arcmin and  $\Delta t$  varied from 27 to 427 ms, thresholds were slightly increased for times greater than 250 ms. When speed was held constant at 2.5 deg/s, participants had increased coherence thresholds for larger values of  $\Delta x$  and  $\Delta t$  (32 arcmin/213 ms) than smaller ones (16 arcmin/107 ms and below). These results suggest that a stimulus made with larger values of  $\Delta x$  and  $\Delta t$  will yield higher thresholds than one with lower values of  $\Delta x$  and  $\Delta t$ , even when they travel at the same speed. Consistent with this, Elleberg et al. (2010) investigated thresholds in 5-year-old children and adults with random Gabor kinematograms, holding speed constant at 1.5 deg/s, and testing  $\Delta x/\Delta t$  values of 6 arcmin/66 ms, 30 arcmin/333 ms, and 60 arcmin/666 ms. In general, as displacements increased, thresholds increased in both

groups. Children were immature at all displacements, but least so at the smallest  $\Delta x$  and  $\Delta t$  values tested. These results caution against characterizing motion stimuli simply by the speed ratio, and point to the importance of investigating the effects of not only speed, but  $\Delta x$  and  $\Delta t$ , on performance during development.

Few studies have examined coherence thresholds as a function of  $\Delta x$  and  $\Delta t$  during human development, but evidence from developing macaques suggest these parameters matter. A longitudinal study by Kiorpes and Movshon (2004) demonstrated in young macaques that coherence thresholds for a given speed vary depending on underlying values of  $\Delta x$  and  $\Delta t$ . For example, a 40-week old macaque could best discriminate stimuli created using  $\Delta x$  values of about 7–12 arcmin, meaning discrimination was optimal for speeds from 1 to 4 deg/s when  $\Delta t$  was 19 ms, speeds from 3 to 6 deg/s when  $\Delta t$  was 37 ms, and speeds from 7 to 11 deg/s when  $\Delta t$  was 56 ms. In other words, psychophysical tuning curves obtained from developing macaques have the same peak when plotted as a function of  $\Delta x$ , but not when plotted as a function of speed. While overall coherence thresholds decreased from 3 weeks to 3 years of age, optimal  $\Delta x$  values also decreased, from 15 to 40 arcmin around 3 weeks to 6–8 arcmin at about 3 years (approximately equivalent to ages from 3 months to 12 years in human development; Boothe, Dobson, & Teller, 1985). Even at 3 years, thresholds were best expressed as a function of  $\Delta x$  rather than speed. A similar pattern was found in macaques studied by Kiorpes et al. (2012).

If the optimal value of  $\Delta x$  decreases with age, this may have important implications for studies of global motion perception with children who are still developing. As smaller values of  $\Delta x$  yield slower speeds, this is a potential mechanism for why sensitivity to slow speeds takes longer to develop in human children. These results also suggest that thresholds measured in two studies that use the same signal dot speeds may vary widely, depending on the value of  $\Delta x$  used in the RDK stimulus. Children may appear more or less mature for a given speed, depending on the  $\Delta x$  used by the experimenter. The goal of this experiment was get a better understanding of how changes in  $\Delta x$  and  $\Delta t$  impact motion coherence thresholds.

The values selected in this experiment were chosen to closely match those used by Kiorpes and Movshon (2004), who tested an approximately logarithmic progression of  $\Delta x$  values from 1 to 60 arcmin, and  $\Delta t$  values of 19 ms, 37 ms, and 56 ms. In pilot studies with adults it was determined that some people have difficulties seeing motion from  $\Delta x$  displacements greater than 40 arcmin at longer values of  $\Delta t$ , so a range from 1 to 38 arcmin was used. Two  $\Delta t$  values, 17 ms and 50 ms, were selected to be similar to the shortest and longest tested by Kiorpes and Movshon (2004).

## 2. Methods

### 2.1. Participants

Children (4–7 years old) and adults (18–30 years old) were recruited for this experiment. As assessed through self- or parental-report, all participants were free of any visual, neural, developmental, or cognitive disorders that might impact performance or interfere with binocular vision. Stereo and visual acuities for each participant were assessed before the experiment began.

A total of 33 children were recruited (22 female;  $M$  age = 5.6 years;  $SD$  = 0.9, range 4.0–7.0). All children had a stereoacuity score on the Randot Preschool Stereoacuity Test (Stereo Optical Co., Inc.) that was better than the normal limit for their age (200 arcsec for 4–5 year olds, 100 arcsec for 6 year olds; Birch et al., 2008), and monocular visual acuity scores at 6 m on the Regan high-contrast letter chart (Regan, 1988) that were better than the normal limit

for their age (0.38 LogMAR for 4–5 year olds, 0.30 LogMAR for 6 year olds; Dobson et al., 2009). The PattiPics Symbol Chart (Precision Vision) was used to assess visual acuity in three children who could not reliably identify letters. Two children were excluded for difficulties attending to the task, two children were excluded for failing to achieve at least 5/8 correct on a series of preliminary practice trials (described below); and one child was excluded for being at risk for amblyopia, indicated by a 0.20 LogMAR difference in visual acuity between the eyes, which may affect motion processing (Ho & Giaschi, 2006). This left 28 children for analysis.

A total of 42 adults were recruited (20 female;  $M$  age = 21.9 years,  $SD$  = 3.1, range 18.3–29.5). All adults included in the analysis achieved a stereoacuity score of 40 arcsec (Birch et al., 2008), and monocular visual acuity scores of 0.10 LogMAR or better. Five adults were excluded for poor stereoacuity, five were excluded for poor visual acuity, and one was excluded for failing to achieve at least 5/8 correct on a series of preliminary practice trials. This left 31 adults for analysis.

## 2.2. Apparatus

Stimulus presentation was controlled by an Intel Core i7 Macintosh Macbook Pro running MATLAB R2008b (The MathWorks, Inc.) with the Psychophysics Toolbox extension version 3.0.10 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Stimuli were presented on a BenQ XL2420T LED-backlit LCD monitor (Lagroix, Yanko, & Spalek, 2012) at a resolution of  $1920 \times 1080$  and a refresh rate of 60 Hz. Participants were seated 1 m from the monitor in a dimly-lit room. Responses were collected with a Logitech gamepad.

## 2.3. Stimuli and experimental conditions

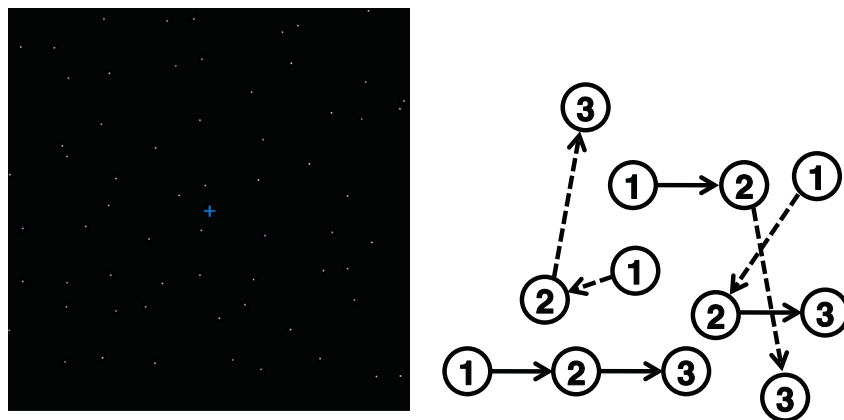
The parameters of the RDK stimulus used in this study were selected to closely match those used by Kiorpes and Movshon (2004). White dots (1 arcmin in diameter;  $270 \text{ cd/m}^2$ ) were presented on a black ( $0.7 \text{ cd/m}^2$ ) background. An array of 64 dots subtended a  $7.7 \times 7.7$  deg square area, for a density of 1.1 dots/deg<sup>2</sup> each frame. The total duration of an animation was 600 ms. Signal dots moved either to the left or to the right, and a white noise algorithm was used to control the movement of dots (see Fig. 1).

This experiment crossed two factors:  $\Delta t$ , the duration of a single animation frame; and  $\Delta x$ , the spatial offset a signal dot was dis-

placed between frames. Two values of  $\Delta t$  were tested: 17 ms and 50 ms. In the 17 ms condition, animation frames were replaced at a rate equal to the refresh rate of the monitor (60 Hz). To achieve the total duration of 600 ms, this stimulus consisted of 36 animation frames total. In the 50 ms condition, animation frames were replaced at a rate of 20 Hz (every three monitor refreshes), for a total of 12 frames. Seven values of  $\Delta x$  were tested, ranging from 1 to 38 arcmin. The combination of these parameters created motion speeds ranging from 1 to 38 deg/s in the 17 ms condition, and from 0.3 to 13 deg/s in the 50 ms condition (see Table 1). Adults participated in all possible conditions of the experiment, and children were randomly assigned to either the 17 ms or 50 ms  $\Delta t$  conditions.

## 2.4. Procedure

The participant's task was to indicate whether they perceived coherent motion to the left or to the right after viewing each RDK. At the beginning of a trial, participants saw a fixation cross, followed by the motion stimulus, followed by a question mark. The task was made child-friendly by introducing a Toy Story themed backstory to provide instructions and frame the psychophysical task as a computer game in which the child had to save characters from being hit by moving stars. A Toy Story character was placed on each side of the screen, and children were asked to indicate which character the stars were moving towards. Feedback was provided by presenting a cartoon character along with an auditory chime for correct responses, and a different cartoon character presented with no sound for incorrect responses. The next trial began upon button-press. The first RDK of a staircase was always presented with 100% coherence. Trial-by-trial coherence was adjusted according to a two-down, one-up staircase procedure, meaning that the coherence value of the next trial was decreased (i.e., made harder) if the participant got two trials correct in a row, or increased (i.e., made easier) if the participant got one trial incorrect. A response reversal occurred when the staircase changed from descending coherence values to ascending ones or vice versa. Coherence was adjusted in steps of 10% until three response reversals occurred, after which step-size halved at each reversal until a minimum step size of 1% was reached. Staircases terminated after 50 trials or 10 response reversals, whichever occurred first. To prevent early mistakes from impacting the range of values reached by the staircase, response reversals at coherence values greater than



**Fig. 1.** The global motion stimulus. *Left:* a single frame of the RDK stimulus. *Right:* a schematic of dot behavior on three subsequent frames of the RDK. Dot movement is governed by a white noise algorithm with signal and noise labels assigned probabilistically, such that on every animation frame, dots are selected to be a signal dot with a probability equal to the coherence value. In this four-dot example, coherence is 0.50; on each frame, two dots are selected at random to be signal dots, and the remaining two are noise dots. Signal dots move in the signal direction (in this example, right) at a fixed spatial offset. Noise dots move in a randomly-selected direction at a randomly-selected spatial offset.

**Table 1**  
Parameters for the temporal (2 levels) and spatial (7 levels) conditions.

	Spatial offset $\Delta x$ (arcmin)						
	1	3	5	11	23	30	38
Temporal offset $\Delta t$ (ms)							
17 ms							
Speed (deg/s)	1	3	5	11	23	30	38
50 ms							
Speed (deg/s)	0.3	1	2	4	8	10	12

80% did not contribute to the step-size halving or staircase termination rules.

At the beginning of a session, participants conducted eight trials of a practice staircase using a  $\Delta x$  of 15 arcmin. Children practiced using the  $\Delta t$  value of the condition to which they were assigned. Because adults participated in both the 17 and 50 ms conditions, the value used in practice was determined randomly. During the experiment, each child completed up to seven staircases within one  $\Delta t$  condition. Children were encouraged to complete all seven staircases, but were not kept longer than 1 h; thus, data were included only for children who could complete at least three conditions during the experimental session. Each adult completed 14 staircases total, one for each  $\Delta t$  by  $\Delta x$  crossing. Condition order was determined by a Latin square. Consistent with previous studies (e.g., Ellemberg et al., 2002; Hadad, Maurer, & Lewis, 2011; Narasimhan & Giaschi, 2012; Parrish et al., 2005), testing was conducted monocularly, using the eye with the best visual acuity (or, when the eyes had the same visual acuity, a randomly-selected eye).

### 2.5. Analysis

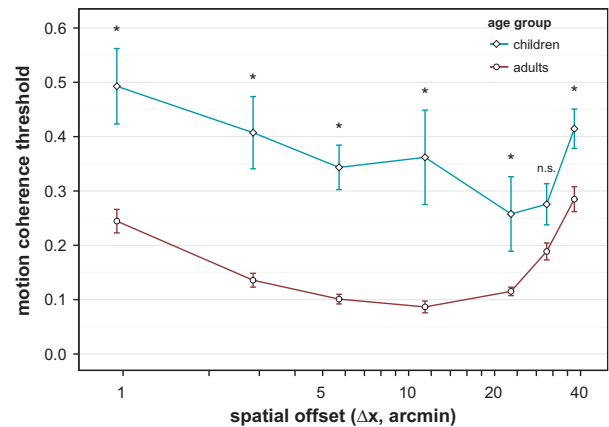
A motion coherence threshold was obtained for each staircase run by fitting a Weibull function to responses using a maximum-likelihood minimization bootstrap procedure (Watson, 1979) and verifying the function fit with a chi-square test. Coherence thresholds are expressed as a proportion, and so can take on a value from 0 (completely random dot motion) to 1 (completely coherent dot motion). The coherence level at the slope of maximum inflection on the Weibull curve, which is at 82% correct for a two-alternative forced-choice task (Strasburger, 2001), was taken as the motion coherence threshold for that run.

Because it is less affected by between-group differences in sample size and variance can handle missing data on a repeated measure, a marginal linear model (also known as a *population-averaged model*; West, Welch, & Galecki, 2007) was used to test main effects and interactions in these analyses. Parameters were estimated with restricted maximum-likelihood estimation (SPSS 21, IBM Corp.). All analyses modeled an unstructured covariance matrix, as no assumptions were made about the form of these matrices. Follow-up procedures (simple main effects) were performed using the same ML framework, and Bonferroni-corrected for a family-wise error rate of  $\alpha = .05$ .

### 3. Results

Developmental differences in coherence thresholds were examined with the between-subjects factor Age Group (2 levels: Child,  $n = 14$ ; and Adult,  $n = 31$ ) and within-subjects factor  $\Delta x$  (7 levels). Analyses were conducted for each  $\Delta t$ : one for the 17 ms condition, and another for the 50 ms condition.

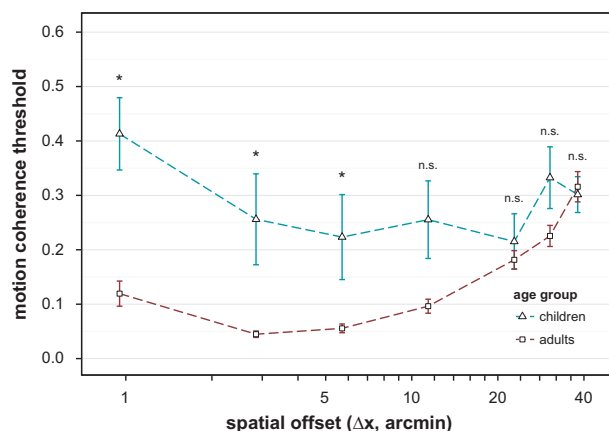
Data for the 17 ms condition are displayed in Fig. 2. There was a significant main effect of Age Group,  $F(1,37.17) = 53.02$ ,  $p < .0001$  and a significant main effect of  $\Delta x$ ,  $F(6,35.06) = 19.23$ ,  $p < .0001$ ,



**Fig. 2.** Motion coherence for children and adults obtained for the 17 ms  $\Delta t$  condition. Error bars reflect standard error. Significant differences between children and adults are indicated with asterisks (Bonferroni family-wise error rate of  $\alpha = .05$ ); n.s. indicates no significant differences.

qualified by a significant Age Group by  $\Delta x$  interaction,  $F(6,35.06) = 3.72$ ,  $p = .0058$ . Simple main effects analysis examining the effect of Age Group at each  $\Delta x$  indicated that adults had significantly lower thresholds than children for six of seven  $\Delta x$  values, 1 arcmin:  $F(1,40) = 20.77$ ,  $p < .0004$ , 3 arcmin:  $F(1,42) = 33.83$ ,  $p < .0001$ , 6 arcmin:  $F(1,45) = 74.03$ ,  $p < .0001$ , 11 arcmin:  $F(1,47) = 22.71$ ,  $p < .0002$ , 23 arcmin:  $F(1,45) = 11.52$ ,  $p = .011$ , 38 arcmin:  $F(1,45) = 8.59$ ,  $p = .039$ . There was no significant difference between adults and children for a  $\Delta x$  of 30 arcmin,  $F(1,46) = 6.36$ ,  $p = .10$ .

Data for the 50 ms condition are displayed in Fig. 3. There was a significant main effect of Age Group,  $F(1,39) = 11.81$ ,  $p = .0014$ , a



**Fig. 3.** Motion coherence thresholds for children and adults obtained for the 50 ms  $\Delta t$  condition. Error bars reflect standard error. Significant differences between children and adults are indicated with asterisks (Bonferroni family-wise error rate of  $\alpha = .05$ ); n.s. indicates no significant differences.

significant main effect of  $\Delta x$ ,  $F(6, 39.33) = 20.33$ ,  $p < .0001$ , qualified by a significant Age Group by  $\Delta x$  interaction,  $F(6, 39.33) = 8.73$ ,  $p < .0001$ . Simple main effects analysis revealed adults had significantly lower thresholds than children in the 1 arcmin ( $F(1, 41) = 18.78$ ,  $p < .0001$ ), 3 arcmin ( $F(1, 41) = 13.05$ ,  $p = .0070$ ), 6 arcmin ( $F(1, 41) = 11.54$ ,  $p = .014$ ) conditions, but thresholds were not significantly different between adults and children in the 11 arcmin ( $F(1, 41) = 7.44$ ,  $p = .063$ ), 23 arcmin ( $F(1, 42) = 0.13$ ,  $p = 1$ ), 30 arcmin ( $F(1, 43) = 5.89$ ,  $p = .14$ ), and 38 arcmin ( $F(1, 41) = 0.11$ ,  $p = 1$ ) conditions.

To facilitate comparisons between adults and children as a function of speed, Fig. 4 presents the child and adult data from Figs. 2 and 3 on one graph, plotted as a function of speed.

#### 4. Discussion

The results of the current study indicate that children can be considered mature, or not, depending on the  $\Delta t$  and  $\Delta x$  values that underlie a RDK. For a  $\Delta t$  of 17 ms, all but one  $\Delta x$  value tested (30 arcmin; corresponding to a speed of 30 deg/s) showed significant differences in coherence thresholds between children and adults. For a  $\Delta t$  of 50 ms, children had significantly higher motion coherence thresholds than adults at  $\Delta x$  values of 6 arcmin and below (corresponding to speeds of 2 deg/s and slower). However, there were no significant differences between children and adults for  $\Delta x$  values of 11 arcmin and above (corresponding to speeds of 4 deg/s and faster). This is consistent with previous research that found children mature earlier for fast than for slow motion tasks (e.g., Narasimhan & Giaschi, 2012). Importantly, there were some intermediate speeds (4–12 deg/s) for which we found that children performed like adults in the longer 50 ms condition, but not in the shorter 17 ms condition. This suggests that maturity cannot be predicted from the speed of the motion stimulus alone (Fig. 4).

This finding can resolve some of the inconsistencies identified in the literature, as it predicts the pattern of maturity observed in previous experiments. For example, Hadad, Maurer, and Lewis (2011) used a  $\Delta t$  of 13 ms. Similar to the children in the 17 ms condition in the current study, they found children around the same age were immature at speeds of 4 and 18 deg/s. Narasimhan and Giaschi (2012) used a  $\Delta t$  of 40 ms, which is between the two values tested in this study. Consistent with the current results, they found children were immature for speeds of 1 deg/s, and closer to maturity at speeds of 4 deg/s.

Two additional studies that demonstrated mature performance in 6-year-olds require some consideration. First, there is some

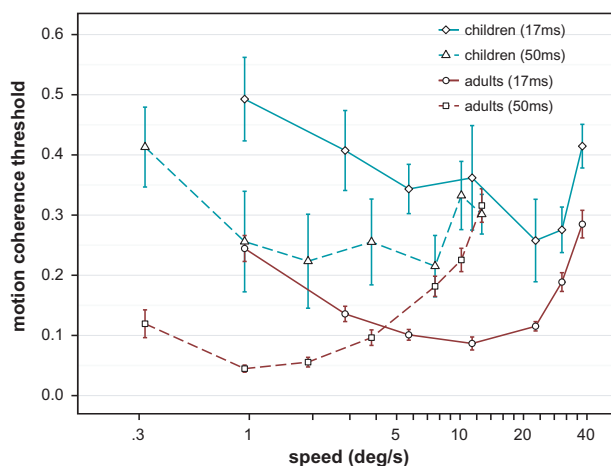


Fig. 4. The data from Figs. 2 and 3 plotted as a function of speed, rather than  $\Delta x$ .

uncertainty about the stimulus parameters used in Ellemberg et al. (2002). If the signal dots had unlimited lifetimes and the noise dots had limited lifetimes, as suggested by Hadad, Maurer, and Lewis (2011), their task may have been easier for children than the current task. Second, Reiss, Hoffman, and Landau (2005) found that children were mature in a motion detection task using  $\Delta x$  of 7.5 arcmin and  $\Delta t$  of 50 ms (for a speed of 2.51 deg/s), using a  $\Delta x$  of 7.5 arcmin. While the same algorithm for dot movement was used in both that study and the current study, the former used a detection task, rather than a discrimination task.

The current study tested only two values of  $\Delta t$ , and found mature performance for 4 of 7  $\Delta x$  conditions when  $\Delta t = 50$  ms, compared to 1 of 7  $\Delta x$  conditions when  $\Delta t = 17$  ms. Thus, it may also be that children are more mature as values of  $\Delta t$  increase. This would be consistent with the findings of Parrish et al. (2005), who used a  $\Delta t$  of 107 ms, and found children had mature motion coherence thresholds at a speed of 1.2 deg/s. Ellemberg et al. (2010), using random Gabor kinematograms, held speed constant at 1.5 deg/s and tested  $\Delta t$  values of 66 ms, 333 ms, and 666 ms. They found children were less mature at the larger two values of  $\Delta t$ . Taken together, the results of these studies suggest that, as a function of  $\Delta t$ , children may have lowest motion coherence thresholds somewhere between 100 and 300 ms, with higher thresholds for  $\Delta t$  values below and above this range, but this requires further investigation.

While the 50 ms condition of the current experiment revealed mature performance in children for  $\Delta x$  of 11 arcmin and larger, children may not necessarily appear more adult-like as spatial offset increases beyond the values tested here. For example, the maximum  $\Delta x$  that is perceived as motion ( $D_{max}$ ) is about 58 arcmin for children 5–6 years old, and about 73 arcmin for adults (Parrish et al., 2005) for an 8-frame stimulus with a  $\Delta t$  of 107 ms. As  $\Delta x$  reaches and exceeds children's maximum  $\Delta x$  displacement thresholds, they are expected to perform worse than adults. At a spatial offset of 65 arcmin, for example, young children may not even perceive motion at 100% coherence, even if adults do.

It should be noted that the current study controlled for stimulus duration, and not number of animation frames. Here, the 17 ms condition presented 36 total frames, and the 50 ms condition presented 12 total frames. If 12 frames were not enough for children to perform well, we might expect to see lower coherence thresholds for children in the 17 ms condition, or for children in the 17 ms condition to appear more mature than children in the 50 ms. Like increasing the dot density of a stimulus, which has shown to impact thresholds in children but not adults (Narasimhan & Giaschi, 2012), increasing the total presented animation frames may lead to more adult-like performance in children. However, this does not appear to be the case, and children's performance is slightly better, if not the same, in the 50 ms condition.

While the current study, and others (e.g., Ellemberg et al., 2002; Hadad, Maurer, & Lewis, 2011; Narasimhan & Giaschi, 2012; Parrish et al., 2005), measured monocular motion coherence thresholds, many studies of development measure thresholds binocularly (e.g., Ellemberg et al., 2004, 2010). In adults, Hess et al. (2007) found a binocular advantage only for low-contrast stimuli. As far as we know, no studies have directly compared monocular to binocular motion coherence thresholds during development. However, we found similar thresholds in two previous studies with 10 year olds, one with binocular viewing (Edwards et al., 2004) and one with monocular viewing (Parrish et al., 2005).

Mounting evidence suggests there may be separate systems for perceiving slow (below 3 deg/s) and fast motion, with considerable overlap at intermediate speeds (e.g., Burr, Fiorentini, & Morrone, 1998; Edwards, Badcock, & Smith, 1998; Gorea, Papathomas, & Kovács, 1993; Heinrich et al., 2004; Khuu & Badcock, 2002; Thompson, Brooks, & Hammett, 2006; van der Smagt, Verstraten, & Van de

Grind, 1999). Based on psychophysical evidence, some authors argue slow motion information may be carried by the parvocellular or ventral stream, whereas fast motion information is carried by the magnocellular or dorsal stream (van de Grind et al., 2001; Verstraten, van der Smagt, & van de Grind, 1998). Gegenfurtner and Hawken (1996) have suggested that a pathway through V1 to V3 and V4 may carry slow motion information. Neuroimaging evidence is beginning to support a cortical basis for ventrally-carried slow speed information. For example, using electroencephalography, Lorteije, van Wezel, and van der Smagt (2008) found ventral areas activated for stimuli moving at slow speeds (3.5 deg/s) and dorsal areas activated for both slow and fast speeds (32 deg/s). The results from the current experiment suggest that if slow speeds are carried by different brain areas than fast speeds, it may be because of the smaller spatial offsets used in the RDKs.

If slow speed is carried ventrally, this might account for the prolonged development of slow motion sensitivity – if ventral areas do indeed take longer to mature. Evidence on which processing stream matures first is inconsistent. Mitchell and Neville (2004) measured ERP components in 6- to 10-year-olds and adults to isoluminant color stripes (a “ventral” stimulus) and moving gratings (a “dorsal” stimulus) and found ERPs for the dorsal stimulus displayed more immaturities. Langrová et al. (2006) measured pattern-reversal and motion-onset visual evoked potentials and came to similar conclusions. In contrast, Dekker et al. (2011) studied the same age group using functional magnetic resonance imaging to measure responses to tools in dorsal areas and animal faces in ventral areas, and found activation patterns in dorsal areas, but not ventral areas, were adult-like. Studies of the structural neurological pathways in developing macaques suggest dorsal motion and parietal pathways mature earlier than the ventral temporal pathways involved in form and object perception (Distler et al., 1996). Of course, development is likely nuanced throughout the brain: areas within a single processing stream may mature at different rates.

## 5. Conclusion

The current study measured global motion direction discrimination thresholds in children and adults for a range of speeds by testing seven spatial offsets ( $\Delta x$ ) at two temporal offsets ( $\Delta t$ ). We found that thresholds in adults and children were better described as a function of  $\Delta x$  rather than of speed. We demonstrated that children can be considered immature at slow speeds and mature at fast speeds when  $\Delta t$  was longer. Whether they were mature at intermediate speeds (4–12 deg/s) depended on the values of  $\Delta x$  and  $\Delta t$  in the speed ratio. For larger values of  $\Delta x$  (and thus  $\Delta t$ ), children performed no different from adults. This has resolved previous inconsistencies in research on the maturation of global motion perception by suggesting a framework in which to place comparisons between child and adult performance. These results caution experimenters to carefully report the parameters they use to study global motion maturation.

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## References

Ahmed, I. J., Lewis, T. L., Ellemberg, D., & Maurer, D. (2005). Discrimination of speed in 5-year-olds and adults: Are children up to speed? *Vision Research*, 45, 2129–2135.

- Arena, A., Hutchison, C. V., & Shimozaki, S. S. (2012). The effects of age on the spatial and temporal integration of global motion. *Vision Research*, 58, 27–32.
- Birch, E., Williams, C., Drover, J., Fu, V., Cheng, C., Northstone, K., et al. (2008). Randot preschool stereoacuity test: Normative data and validity. *Journal of the American Association for Pediatric Ophthalmology and Strabismus*, 12, 23–26.
- Boothe, R. G., Dobson, M. V., & Teller, D. Y. (1985). Postnatal development of vision in human and nonhuman primates. *Annual Review of Neuroscience*, 8, 495–545.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, 10, 433–436.
- Burr, D. C., Fiorentini, A., & Morrone, C. (1998). Reaction time to motion onset of luminance and chromatic gratings is determined by perceived speed. *Vision Research*, 38, 3681–3690.
- Dekker, T., Mareschal, D., Sereno, M. I., & Johnson, M. H. (2011). Dorsal and ventral stream activation and object recognition performance in school-age children. *NeuroImage*, 57, 659–670.
- Distler, C., Bachevalier, J., Kennedy, C., Mishkin, M., & Ungerleider, L. G. (1996). Functional development of the corticocortical pathway for motion analysis in the macaque monkey: A 14C-2-deoxyglucose study. *Cerebral Cortex*, 6, 184–195.
- Dobson, V., Clifford-Donaldson, C. E., Green, T. K., Miller, J. M., & Harvey, E. M. (2009). Normative monocular visual acuity for early treatment diabetic retinopathy study charts in emmetropic children 5 to 12 years of age. *Ophthalmology*, 116, 1397–1401.
- Edwards, M., Badcock, D. R., & Smith, A. T. (1998). Independent speed-tuned global-motion systems. *Vision Research*, 38, 1573–1580.
- Edwards, V., Giaschi, D., Dougherty, R., Edgell, D., Bjornson, B., Lyons, C., et al. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology*, 25, 321–354.
- Ellemberg, D., Lewis, T. L., Dirks, M., Maurer, D., Ledgeway, T., Guillemot, J. P., et al. (2004). Putting order into the development of sensitivity to global motion. *Vision Research*, 44, 2403–2411.
- Ellemberg, D., Lewis, T. L., Maurer, D., Brar, S., & Brent, H. P. (2002). Better perception of global motion after monocular than after binocular deprivation. *Vision Research*, 42, 169–179.
- Ellemberg, D., Lewis, T. L., Maurer, D., Lee, B., Ledgeway, T., Guillemot, J. P., et al. (2010). The effect of displacement on sensitivity to first- and second-order global motion in 5-year-olds and adults. *Seeing and Perceiving*, 23, 517–532.
- Gegenfurtner, K. R., & Hawken, M. J. (1996). Interaction of motion and color in the visual pathways. *Trends in Neurosciences*, 19, 394–401.
- Gorea, A., Papathomas, T. V., & Kovács, I. (1993). Two motion systems with common and separate pathways for color and luminance. *Proceedings of the National Academy of Sciences of the United States of America*, 90, 11197–11201.
- Hadad, B., Maurer, D., & Lewis, T. L. (2011). Long trajectory for the development of sensitivity to global and biological motion. *Developmental Science*, 14, 1330–1339.
- Hayward, J., Truong, G., Partanen, M., & Giaschi, D. (2011). Effects of speed, age and amblyopia on the perception of motion defined form. *Vision Research*, 51, 2216–2223.
- Heinrich, S. P., van der Smagt, M. J., Bach, M., & Hoffmann, M. B. (2004). Electrophysiological evidence for independent speed channels in human motion processing. *Journal of Vision*, 4, 469–475.
- Hess, R. F., Hutchinson, C. V., Ledgeway, T., & Mansouri, B. (2007). Binocular influences on global motion processing in the human visual system. *Vision Research*, 47, 1682–1692.
- Ho, C. S., & Giaschi, D. E. (2006). Deficient maximum motion displacements in amblyopia. *Vision Research*, 46, 4595–4603.
- Khuu, S. K., & Badcock, D. R. (2002). Global speed processing: Evidence for local averaging within, but not across two speed ranges. *Vision Research*, 42, 3031–3042.
- Kiorpes, L., & Movshon, J. A. (2004). Development of sensitivity to visual motion in macaque monkeys. *Visual Neuroscience*, 21, 851–859.
- Kiorpes, L., Price, T., Hall-Haro, C., & Movshon, J. A. (2012). Development of sensitivity to global form and motion in macaque monkeys (*Macaca nemestrina*). *Vision Research*, 63, 34–42.
- Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception*, 36, ECVF Abstract Supplement.
- Lagroix, H. E., Yanko, M. R., & Spalek, T. M. (2012). LCDs are better: Psychophysical and photometric estimates of the temporal characteristics of CRT and LCD monitors. *Attention, Perception, and Psychophysics*, 74, 1033–1041.
- Langrová, J., Kuba, M., Kremláček, J., Kubová, Z., & Vít, F. (2006). Motion-onset VEPs reflect long maturation and early aging of visual motion-processing system. *Vision Research*, 46, 536–544.
- Lorteije, J. A. M., van Wezel, R. J. A., & van der Smagt, M. J. (2008). Disentangling neural structures for processing of high- and low-speed visual motion. *European Journal of Neuroscience*, 27, 2341–2353.
- Manning, C., Aagten-Murphy, D., & Pellicano, E. (2012). The development of speed discrimination abilities. *Vision Research*, 70, 27–33.
- Milne, E., Swettenham, J., Hansen, P., Campbell, R., Jeffries, H., & Plaisted, K. (2002). High motion coherence thresholds in children with autism. *Journal of Child Psychology and Psychiatry*, 43, 255–263.
- Mitchell, T. V., & Neville, H. J. (2004). Asynchronies in the development of electrophysiological responses to motion and color. *Journal of Cognitive Neuroscience*, 16, 1363–1374.
- Narasimhan, S., & Giaschi, D. (2012). The effect of dot speed and density on the development of global motion perception. *Vision Research*, 62, 102–107.

- Parrish, E. E., Giaschi, D. E., Boden, C., & Dougherty, R. (2005). The maturation of form and motion perception in school age children. *Vision Research*, 45, 827–837.
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, 10, 437–442.
- Regan, D. (1988). Low contrast letter charts and sinewave grating tests in ophthalmological and neurological disorders. *Clinical Vision Science*, 2, 235–250.
- Reiss, J. E., Hoffman, J. E., & Landau, B. (2005). Motion processing specialization in Williams syndrome. *Vision Research*, 45, 3379–3390.
- Silverman, S. E., Tran, D. B., Zimmerman, K. M., & Feldon, S. E. (1994). Dissociation between the detection and perception of motion in Alzheimer's disease. *Neurology*, 44, 1014–1018.
- Snowden, R. J., & Kavanagh, E. (2006). Motion perception in the ageing visual system: Minimum motion, motion coherence, and speed discrimination thresholds. *Perception*, 35, 9–24.
- Strasburger, H. (2001). Converting between measures of slope of the psychometric function. *Perception and Psychophysics*, 63, 1348–1355.
- Taylor, N. M., Jakobson, L. S., Maurer, D., & Lewis, T. L. (2009). Differential vulnerability of global motion, global form, and biological motion processing in full-term and preterm children. *Neuropsychologia*, 47, 2766–2778.
- Thompson, P., Brooks, K., & Hammett, S. T. (2006). Speed can go up as well as down at low contrast: Implications for models of motion perception. *Vision Research*, 46, 782–786.
- van de Grind, W. A., van Hof, P., van der Smagt, M. J., & Verstraten, F. A. J. (2001). Slow and fast visual motion channels have independent binocular-rivalry stages. *Proceedings of the Royal Society B: Biological Sciences*, 268, 437–443.
- van der Smagt, M. J., Verstraten, F. A. J., & Van de Grind, W. A. (1999). A new transparent motion aftereffect. *Nature Neuroscience*, 2, 595–596.
- Verstraten, F. A. J., van der Smagt, M. J., & van de Grind, W. A. (1998). Aftereffect of high-speed motion. *Perception*, 27, 1055–1066.
- Watson, A. B. (1979). Probability summation over time. *Vision Research*, 19, 515–522.
- West, B., Welch, K. B., & Galecki, A. T. (2007). *Linear mixed model: A practical guide using statistical software*. Florida: Chapman Hall/CRC Press.