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Sensitivity to first- and second-order motion and form in children and adults

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ABSTRACT

We compared the sensitivity of adults and children aged 3–10 years to first- and second-order motion and form. For first-order stimuli, at all ages sensitivity was better for motion than form, and motion thresholds were better at 6 Hz than at 1.5 Hz. For second-order stimuli, at all ages sensitivity was better for form than motion, and motion thresholds were better at 0.25 cyc/deg than at 1 cyc/deg. Thresholds became adult-like later for motion than for form and later for first-order than second-order stimuli. For first-order stimuli, the changes with age were larger and more protracted.

1. Introduction

Cues to motion are provided by any physical parameter for which spatial location varies with time. Changes in boundaries that are defined by luminance are a first-order cue to motion. Changes in boundaries that are defined by parameters other than luminance, such as contrast or texture, are a second-order cue to motion. Fig. 1 shows an example of stationary gratings defined by first-order (Panel A) and second-order (Panel B) cues to pattern.

A large body of evidence indicates that the mechanisms that process first- and second-order cues to motion are, in part, separate. For example, adults do not integrate alternating frames containing first- and second-order cues to local motion into an unambiguous percept of motion (Ledgeway & Smith, 1994a), and their sensitivity to first- or second-order local motion is not affected by adaptation to motion of the other type (Nishida, Ledgeway, & Edwards, 1997). Further, both the latency of the visual evoked potential and the reaction time for a psychophysical response are longer for the onset of second-order motion than for the onset of first-order motion (Ellemberg, Lavoie et al., 2003). In addition, a functional magnetic resonance imaging (fMRI) study demonstrated a clear segregation between the neural areas that are active during the processing of first- and second-order motion: first-order motion most strongly activated early visual areas (V1) whereas second-order motion most strongly activated higher visual areas near V5 (Dumoulin, Baker, Hess, & Evans, 2003). Later, researchers found that the fMRI signal adapts when the same direction of motion is repeated but only when both the original and repeated motion is of the same type (both first-order or both second-order) (Ashida, Lingnau, Wall, & Smith, 2007).

Both first- and second-order motion can be either local or global. Local motion involves motion of a stimulus or segment of a stimulus that is unidirectional and can be signaled correctly by a single receptive field. In contrast, the perception of global motion requires the integration of local motion signals across a stimulus and can involve more complex stimuli with more than one direction of local motion that must be integrated to create a predominate direction.

While many studies have examined the development of sensitivity to global motion (e.g., Banton, Berthenthal, & Seaks, 1999; Banton, Dobkins, & Berthenthal, 2001; Parrish, Giaschi, Boden, & Dougherty, 2005), relatively little is known about the development of sensitivity to local motion. Sensitivity to local motion is commonly measured using contrast thresholds. This is defined as the minimum difference in luminance (for first-order stimuli) or contrast (for second-order stimuli) between adjacent stripes required for the observer to accurately discriminate direction of motion. To date, only three studies have examined sensitivity to both first- and second-order local motion in typically developing children and adults. In the first, Ellemberg, Lewis et al. (2003) measured sensitivity to the direction of first- and second-order local motion in adults and 5-year-olds by measuring contrast thresholds for discriminating leftward from rightward drifting gratings. They reported that 5-year-olds' thresholds were worse than those of adults' regardless of motion type, but the difference between

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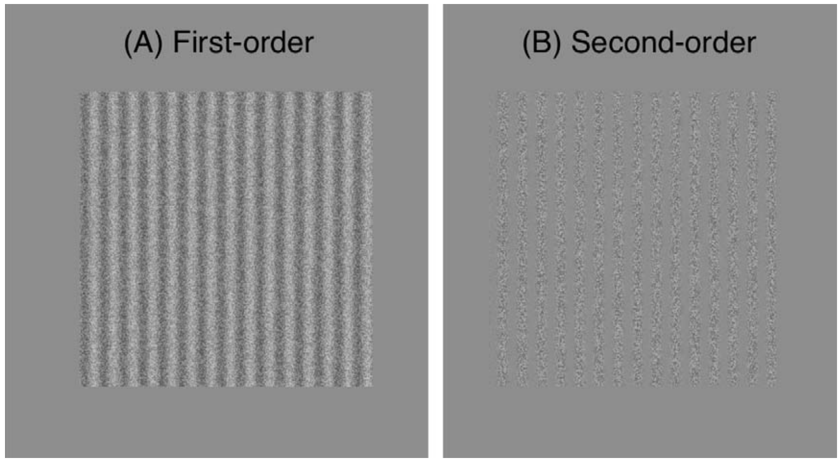

Fig. 1. An example of first-order and second-order stimuli. (A) First-order grating defined by luminance cues. High luminance stripes alternate with low luminance stripes. (B) Second-order grating defined by contrast cues. High contrast stripes composed of black and white pixels alternate with low contrast stripes composed of lighter and darker grey pixels. The mean luminance of adjacent stripes is the same.

5-year-olds' and adults' thresholds was greater for second-order motion than for first-order motion, a pattern suggesting that sensitivity to second-order motion may be slower to mature.

In a study using similar methods, Bertone, Hanck, Cornish, and Faubert (2008) measured sensitivity to the direction of first- and second-order local motion in children ranging from 5 to 10 years of age. In agreement with Ellemberg, Lewis et al. (2003), Bertone et al. reported that at 5–6 years of age, children's sensitivity to second-order motion was more immature than their sensitivity first-order motion. However, they also reported that sensitivity to second-order motion became adult-like by 7–8 years age, an age at which sensitivity to first-order motion was still not mature.

In the third study, Thibault, Brosseau-Lachaine, Faubert, and Vital-Durand (2007) measured sensitivity to first- and second-order drifting gratings in children ranging from less than 1 year to almost 7 years of age. Children viewed a drifting grating paired with a static grey-scale noise field. Over trials, the visibility of the grating was varied using the method of constant stimuli. Using a forced-choice preferential looking method, a trained observer judged the position of the drifting grating (left or right) based on the child's eye gaze. Unlike the other two studies (Bertone et al., 2008; Ellemberg, Lewis et al., 2003), Thibault et al. reported that thresholds for drifting versus static stimuli improved at an equal rate for first- and second-order stimuli. However, because the stimuli were a drifting grating versus static noise, the looking preferences measured by Thibault et al. may have been based on the detection of the stripes in the grating or the flicker created as it moved, rather than its direction of motion. Nevertheless, together, the results from the three studies describing the trajectory of development for sensitivity to first-order versus second-order motion raise the possibility that the relative rates of development may not be constant across childhood.

In the current study, our first goal was to measure children's sensitivity to the direction of first-order and second-order motion across a wide age range. To do so, we measured sensitivity to the direction of first- and second-order motion in children at ages 3, 5, 7, and 10 years, and in adults. In each case, we compared children's thresholds to those of adults' for the same type of motion, and then compared those patterns for first- versus second-order motion. We did not compare first- and second-order thresholds directly because they are based on different image attributes, and thus, the absolute differences in thresholds are not meaningful (Bertone et al., 2008). Also of interest is how the parameters of temporal frequency, spatial frequency, and velocity affect sensitivity to motion in children compared to adults. These parameters are known to affect adults' sensitivity to motion. For example, the minimum stimulus duration required to discriminate the direction of both first- and second-order motion increases as temporal frequency increases (Ledgeway & Hess, 2002). Furthermore, temporal and spatial sensitivity functions differ for first and second-order stimuli. They are bandpass for first-order motion and lowpass for second-order motion (Hutchinson & Ledgeway, 2006).

In a study of the effect of velocity and temporal frequency on children's sensitivity to the direction of first- and second-order local motion, Ellemberg, Lewis et al. (2003) reported that the difference between thresholds in 5-year-olds and adults varied with temporal frequency and/or velocity, but only for second-order stimuli. Because both temporal frequency and velocity varied together, it was not possible to determine which parameter or parameters were responsible for this difference. Distinguishing the effects of temporal frequency, spatial frequency, and velocity at each age for each type of motion was our second goal. To do so, we tested three conditions for each motion type, using key comparisons on each dimension so that each parameter was equated across two of the three conditions (see Fig. 2). The particular values were similar to those in Ellemberg et al., who used a spatial frequency of 1 cyc/deg, temporal frequencies of 1.5 and 6 Hz, and velocities of 1.5 and 6 deg/s. For each set of parameters, we varied modulation depth across trials to determine the minimum luminance (first-order) or contrast (second-order) for which observers could correctly identify the direction of local motion.

Our final goal was to ensure that children's sensitivity to direction of motion was not limited by poor sensitivity to the pattern of the moving stimulus. If children are unable to see the form of the stimulus, then they may have reduced sensitivity to its motion, even if the motion mechanisms *per se* are adult-like. We measured sensitivity to first- and second-order form in children using a horizontal/vertical discrimination task. On each trial, a stationary grating was presented in a horizontal or a vertical orientation. The task was to indicate the orientation of the grating (horizontal or vertical). Modulation depth was varied over trials to determine the minimum amplitude for which observers could identify correctly the orientation of the grating. We then compared the pattern of thresholds across age for the form task to those for the motion task with the same spatial frequency.

For 5-year-olds, 7-year-olds, 10-year-olds, and adults, participants were asked to indicate the direction of motion (left/right) or orientation of the grating (horizontal/vertical) and received auditory and visual feedback about the accuracy of their responses. Modulation depth varied over trials to determine an individual threshold for each condition for each participant. To extend the developmental trajectory to a younger age, we added toy animals as reinforcers for the 3-year-olds and shortened the procedure. Because, as in all developmental studies, there is no way to ensure that the procedure is equally sensitive at all ages, our conclusions are based on comparisons of the pattern of results across age, and over different conditions.

2. Methods

2.1. Participants

The final sample consisted of 280 participants, 56 in each of the following five age groups: 3-year-olds (range = 3.5–3.75 yrs), 5-year-olds (5.0 yrs ± 3 mo), 7-year-olds (7.0 yrs ± 3 mo), 10-year-olds (10.0 yrs ± 3 mo), and adults (median age = 18 yrs, range 18–21 yrs). Adults were recruited from a pool of undergraduate students registered in Introductory Psychology at McMaster University and received research participation credits in their class grade. Children were recruited using contact information provided by parents who expressed interest in participating in our studies at the time of the child's birth. Most children had participated in other unrelated studies at McMaster University. All participants in the final sample had normal visual histories according to self or parental report and all wore optical correction, if prescribed.[1]

An additional 30 participants were excluded from the final sample because they were uncooperative (16 3-year-olds, seven 5-year-olds, and one 7-year-old), because they failed a criterion designed to test understanding of the task (six 3-year-olds), or because the parent looked at the stimuli and may have influenced the child's responses (four 3-year-olds; see Procedure).

2.2. Apparatus and stimuli

The stimuli were generated by an Apple Macintosh G4 computer by means of VPixx software™ and were displayed on a 53.3 cm Sony Trinitron Monitor. The monitor had a frame rate of 75 Hz and pixel resolution of 1024 × 768. The stimulus was a sinusoidal grating contained within a 15 × 15 deg square at a viewing distance of 50 cm (absolute size: 13.2 × 13.2 cm square). For motion tests, the grating was vertical and drifted to the left or to the right. For form tests, the grating remained stationary and was either horizontal or vertical.

Grating velocities and spatial frequencies are shown in Fig. 2. Because temporal frequency is the product of spatial frequency and velocity (TF = SF × V), changing one value, while holding another constant, results in a change of the third parameter. However, with three conditions, each parameter can be equated over two of the conditions. As described in the caption of Fig. 2, Conditions 2 (1.5 = 1 × 1.5) and 3 (1.5 = 0.25 × 6) had equal temporal frequencies, Conditions 1 (6 = 1 × 6) and 2 had equal spatial frequencies, and Conditions 1 and 3 had equal velocities. This selection of values allowed us to evaluate the separate contributions of temporal frequency, spatial frequency, and velocity.

The gratings were luminance-modulated (first-order) or contrast-modulated (second-order) (see Fig. 1) and were identical to those described by Ellemberg, Lavioe et al. (2003) and Ellemberg, Lewis et al. (2003). The luminance of the stimuli and the background was 10 cd/m^2. The carrier was static two-dimensional unmodulated noise like that described by Smith and Ledgeway (1997). Each noise element subtended 2 × 2 arc min and was assigned independently with a probably of 0.5 to be either 'light' or 'dark'. Prior to modulation, the Michelson contrast of the noise measured over adjacent noise elements with opposite polarity was 29%. For luminance-modulated stimuli, the noise carrier was added to a luminance-modulated sinusoidal grating. This created a series of regions that alternated between higher and lower luminance. The amplitude of the luminance modulation (Michelson contrast or modulation depth) varied within the range of 0–0.5 as defined by:

$$\text{Modulation depth} = (L_{\max} - L_{\min})/L_{\max} + L_{\min}),$$

where $L_{\max}$ and $L_{\min}$ are the maximum and minimum luminances, respectively, averaged over adjacent pairs of noise dots.

For contrast-modulated stimuli, the noise was multiplied by a sine wave to create a contrast-modulated stimulus. The stimulus consisted of a series of alternating regions of higher and lower contrast, with every region having the same mean luminance. The amplitude of the contrast modulation (modulation depth) varied within the range of 0–1 as defined by:

$$\text{Modulation depth} = (C_{\max} - C_{\min})/(C_{\max} + C_{\min}),$$

where $C_{\max}$ and $C_{\min}$ are the maximum and minimum mean local contrast (Michelson) of adjacent pairs of noise. The monitor was calibrated every few weeks to ensure that the luminance of higher and lower contrast regions of the contrast-modulated stimuli differed by less than 1 cd/m^2 and that the mean luminance of the luminance- and contrast-modulated stimuli also differed by no more than 1 cd/m^2 when the gratings were displayed at maximum contrast.

2.3. Procedure

The procedures were explained and informed consent was obtained from adults and from parents of the children. Assent was obtained from the children age 7 and older. The experimental protocol was approved by the McMaster Research Ethics Board.

Each participant was seated 50 cm away from the computer monitor. All but the 3-year-olds sat with their chin positioned on a chin rest, which ensured that a constant testing distance would be maintained. Parents who remained in the testing room were asked to sit out of their child's sight and to remain silent throughout testing. Each participant provided two thresholds, one for first-order and one for second-order stimuli tested in one of the four conditions (the form condition or the motion condition with one of the three combinations of spatial frequency, temporal frequency, and velocity—see Fig. 2). One quarter of the participants at each age completed each of the four conditions.

The 3-year-olds sat in a chair by themselves or, if necessary, on their parent's lap during testing. A chin rest was not used with this age group because it made testing more difficult; however, the experimenter monitored the child's viewing distance throughout the experiment and the child was repositioned as required to keep the distance near 50 cm. As for the older children, parents were asked not to aid in their child's decisions in any way and those holding a 3-year-old during the test were asked to look down at their child rather than at the monitor so that they would be blind to the specific stimulus shown on a trial. Four children were excluded from the final sample because their parents looked at the

[1] Acuity was measured in children 5 years of age and older but not the 3-year-olds and hence was not used as an exclusion criterion. Specifically, for participants older than 5 years of age, we measured monocular linear letter acuity in each eye using the Lighthouse Visual Acuity Chart. For 5-year-olds, we measured monocular acuity in each eye with the Good-lite Crowding cards (Good-lite, catalogue # 1010). Acuity was measured with optical correction, if prescribed. In each age group, acuity was at least 20/20 in the better eye of at least 78% of the participants and at least 20/25 in the better eye of at least 91% of the participants. Within each age group, neither first- nor second-order thresholds were correlated with monocular acuity (all $ps > .05$).

display and tried to help their child. We did not give the parents occluding glasses because they distracted the 3-year-olds.

2.4. Participants 5-years and older

For the direction discrimination task, participants were told that they would see a square containing stripes moving left or right and that the task would be to indicate the direction of movement. For the horizontal/vertical discrimination task, participants were told that they would see a square and that the stripes would be vertical/standing up or horizontal/lying sideways and that the task would be to indicate the orientation of the stripes. In all cases, participants could respond verbally or with hand gestures (e.g., pointing left or right, or holding a hand vertically or horizontally, as required by the task).

At the beginning of each trial, participants were asked to fixate on a 3° black dot that appeared in the centre of the screen. The black dot was then replaced by the stimulus. The experimenter, who could not see the display, watched the participant's eyes to ensure that they were directed toward the computer screen and entered responses on a computer keyboard.

The order of test type (first-order first or second-order first) was counterbalanced across participants within each age group. Prior to testing, participants were presented with two demonstration trials with the gratings at maximum luminance-modulation or contrast-modulation. For each task, the demonstration consisted of one trial for each of the two alternative choices (left/right for motion tasks or horizontal/vertical for the form task). To verify that the participants understood the task, they were presented with a criterion phase consisting of up to three blocks of four test trials, again at maximum modulation depth. To be included in the study, participants had to respond correctly on all four trials in a test block. Participants received verbal feedback for this phase. All participants 5 years and older met this criterion, usually in the first test block.

Upon completion of the criterion phase, participants 5 years and older were given a practice staircase with feedback after each trial. The contrast of the grating(s) was varied over trials using the VPIXX VPEST adaptive staircase that is similar to Harvey's (1986) ML-TEST. Feedback consisted of a high-pitched tone paired with a happy face for a correct response and a low-pitched tone paired with a sad face for an incorrect response. The happy and sad faces appeared in a 15 × 15 deg square in the centre of the monitor and remained on the screen for 250 ms. Practice was terminated after the luminance- or contrast-modulation was reduced to the point where two incorrect responses occurred consecutively. Participants then completed the test phase using the same staircase with the same feedback except that the staircase continued until it terminated when the 95% confidence interval of the estimated threshold was within ±0.1 log units. Thresholds were defined as the minimum luminance-modulation (first-order) or contrast-modulation (second-order) necessary to respond correctly 82% of the time. The entire testing session lasted 30–45 min.

2.5. Three-year-olds

For the motion tasks with 3-year-olds, black boxes were placed on the left and right sides of the computer monitor. When lit from within, a puppy and a monkey were visible in the left and right boxes, respectively. During the demonstration, participants were told that the stripes would go either toward the puppy (for leftward moving stripes) or the monkey (for rightward moving stripes). Each direction was displayed and the appropriate toy was illuminated. The child was then asked to complete the criterion phase to the same standard as the older participants. Three-year-olds responded by pointing to or verbally naming the animal that they thought would light up. The experimenter, who did not know the order of stimulus presentation, stood directly behind the computer monitor so that she could not see the stimuli (and thereby bias the child's response) but still had a full view of the child's eye gaze. As children of this age group almost always looked toward the animal they expected to light up, the direction of eye gaze was used as a check of verbal and pointing responses. Children of this age often looked toward one animal while saying or pointing to another. When eye gaze and other responses were not in agreement, the researcher asked the child, "Which one do you mean, the puppy (pointing to puppy) or the monkey (pointing to monkey)?" This question always disambiguated the response. Gaze direction was used as the key response for a few shyer children who would not point or talk.

For the horizontal/vertical task, the child was given two response cards with black stripes on a white background to aid responding: (1) a transparent, coloured cartoon of a giraffe superimposed on vertical stripes and (2) a transparent, coloured cartoon of a long skinny dog (a 'wiener' dog) superimposed on horizontal stripes. These animals were chosen to give the cards a specific orientation and to match the orientation of the stripes that made up the stimulus: vertical stripes were 'giraffe stripes' and horizontal stripes were 'doggie stripes'. This allowed children to respond by naming the stripes, pointing to the matching card, or even simply looking at the matching card.

The goal of testing was to optimize the performance from all participants, so that the best measures of sensitivity to motion/form could be obtained, regardless of age. Three-year-olds completed the demonstration and criterion phases, but not a practice phase because pilot testing indicated that practice lowered performance on test phases by increasing fatigue for children of this age group. Other than the differences described above in practice, in determining the participants' choice of alternatives, and in the stimuli used for reinforcement, the test phase for 3-year-olds was identical to that for older subjects. A small number of 3-year-olds required two testing sessions, while all other participants completed testing in one session.

3. Results

Thresholds are expressed as logarithmic contrast thresholds. Outliers were replaced using a procedure outlined by Kirk (1999): data points that were ±2.5 standard deviations from the group mean were replaced with the group mean. There were ten outliers: every age group had at least one outlying data point, and no group had more than one outlier. Analyses were conducted separately for first- and second-order stimuli. Absolute differences in first- and second-order thresholds are not meaningful because the thresholds are based on different image attributes (Bertone et al., 2008).

For each type of motion, we conducted a five (age) by three (condition) way ANOVA. To evaluate whether the results could be explained by poor sensitivity to form, we conducted additional 5 (age) by 2 (condition) way ANOVAs comparing the form thresholds to those from the motion conditions using the same spatial frequency, again separately for first- and second-order stimuli. Partial eta squared (η_p^2) values were used for estimates of association strength between the independent and dependent variables. This measure is calculated as follows:

$$\eta_p^2 = SS_{\text{effect}}/(SS_{\text{effect}} + SS_{\text{error}})$$

Unlike classic η^2, it excludes variance attributable to other factors by using $SS_{\text{effect}} + SS_{\text{error}}$ rather than SS_{Total} as the denominator (Pierce, Block, & Aguinis, 2004). For differences analyzed with post hoc *t*-tests, effect size was estimated by calculating Cohen's *d* statistic (Cohen, 1988).

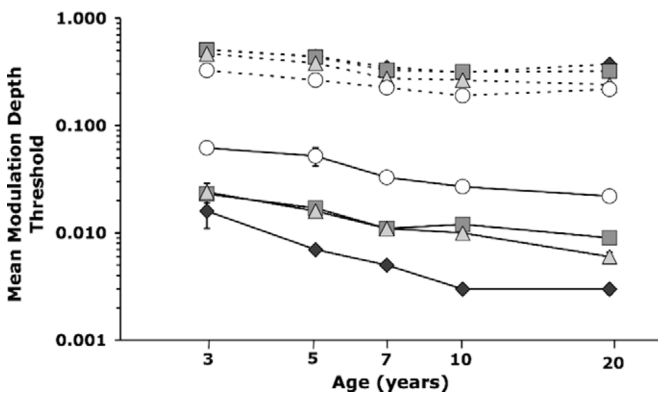

Fig. 2. Mean modulation depth thresholds for first- and second-order motion and form. Thresholds represent the luminance-modulation (solid lines) or contrast-modulation (dashed lines) required to identify the direction of motion (left or right) or orientation of form (horizontal or vertical) with 82% accuracy. The error bars represent ±1 standard error of the mean, and when not shown, are smaller than the symbols. Conditions represent different combinations of temporal frequency (TF), spatial frequency (SF), and velocity (V). TF = SF × V. Symbols represent the following conditions: ◆ 6 = 1 × 6; ■ 1.5 = 1 × 1.5; △ 1.5 = 0.25 × 6; ○ H/V Form.

3.1. First-order motion

A five (age) by three (condition) way ANOVA revealed significant main effects of age, $F(4, 195) = 46.1$, $p < .001$, $\eta_p^2 = .49$, and of condition, $F(2, 195) = 105.7$, $p < .001$, $\eta_p^2 = .52$, but no significant age by condition interaction, $F(8, 195) = 1.3$, $p = .24$, $\eta_p^2 = .05$ (see Fig. 2).

A one-tailed Dunnett's test (Dunnett, 1955) was used to examine the overall effect of age. Children's thresholds were significantly worse than adults' at every age tested (*ps* < .01). Although the age by condition interaction was not significant, it should be noted that the thresholds of 10-year-olds are closer to those of adults in some conditions than in others. For Condition 1 (where TF = SF × V, 6 = 1 × 6), the difference was not significant, $t(26) = 0.6$, $p > .50$, Cohen's $d = 0.2$, while for Condition 2 (1.5 = 1 × 1.5), there was a trend toward a significant difference, $t(26) = 1.9$, $p = .07$, Cohen's $d = 0.72$, and for Condition 3 (1.5 = 0.25 × 6), the difference was significant, $t(26) = 4.3$, $p < .001$, Cohen's $d = 1.56$. The main effect of condition was analyzed using Tukey's HSD (Howell, 2002). The results indicate that the threshold for Condition 1 was better than thresholds for Condition 2 and Condition 3, $t(138) = 13.6$, $p < .001$, Cohen's $d = 1.7$ and $t(138) = 11.4$, $p < .001$, Cohen's $d = 1.3$, respectively, while there was no significant difference between the thresholds for Conditions 2 and 3, $t(138) = 2.2$, $p = .08$, Cohen's $d = 0.3$. Conditions 2 and 3 had equal temporal frequencies of 1.5 Hz, while Condition 1 had a temporal frequency of 6 Hz.

3.2. Second-order motion

The five (age) by three (condition) way ANOVA revealed significant main effects of age, $F(4, 195) = 47.4$, $p < .001$, $\eta_p^2 = .49$, and of condition $F(2, 195) = 26.1$, $p < .001$, $\eta_p^2 = .21$, but no significant age × condition interaction, $F(8, 195) = 1.4$, $p > .20$, $\eta_p^2 = .05$ (see Fig. 2). A one-tailed Dunnett's post hoc analysis revealed that 3- and 5-year-olds' thresholds were significantly higher (worse) than the adults' mean threshold (*ps* < .001) while 7- and 10-year-olds' thresholds were no different than the adults' mean threshold (*ps* > .40). Tukey's post hoc analysis of the effect of condition revealed that thresholds for Conditions 1 and 2 were not different from each other, $t(138) = 1.5$, $p > .30$, Cohen's $d = 0.2$, but both were higher than the threshold for Condition 3, $t(138) = 6.7$, $p < .001$, Cohen's $d = 0.8$ and $t(138) = 5.3$, $p < .001$, Cohen's $d = 0.6$, respectively, for Conditions 1 versus 3 and 2 versus 3. Conditions 1 and 2 had equal spatial frequencies of 1 cyc/deg, while Condition 3 had a spatial frequency of 0.25 cyc/deg.

3.3. First-order form

The results for the Form Condition were compared to the results from the motion conditions with the same spatial frequency, namely, Motion Condition 1 and Motion Condition 2, in two separate five (age) by two (condition) way ANOVAs (see Fig. 2). For Form versus Motion Condition 1, there were significant main effects of age and condition, $F(4, 130) = 35.4$, $p < .001$, $\eta_p^2 = .52$ and $F(1, 130) = 837.5$, $p < .001$, $\eta_p^2 = .87$ for age and condition, respectively, but no significant interaction, $F(1, 130) = 0.8$, $p > .50$, $\eta_p^2 = .02$. A one-tailed Dunnett's test on the form thresholds revealed that mean thresholds for 3-, 5-, and 7-year-olds were significantly worse than the mean threshold for adults (*ps* < .005) while the mean threshold for 10-year-olds was no different than the mean threshold for adults ($p > .05$).

The main effect of condition indicates that thresholds for motion were better than thresholds for form. We found the same pattern of results for the Form Condition versus Motion Condition 2. There were significant main effects of age, $F(4, 130) = 34.1$, $p < .001$, $\eta_p^2 = .51$ and condition, $F(1, 130) = 298.1$, $p < .001$, $\eta_p^2 = .70$, but no significant interaction, $F(4, 130) = 0.6$, $p > .60$, $\eta_p^2 = .02$.

3.4. Second-order form

As in the first-order comparison, the results for the Form Condition were compared to the results from Motion Condition 1 and Motion Condition 2 in two separate five (age) by two (condition) way ANOVAs (see Fig. 2). We found significant main effects of age, $F(4, 130) = 21.8$, $p < .001$, $\eta_p^2 = .4$ and condition $F(1, 130) = 159.0$, $p < .001$, $\eta_p^2 = .55$, but no significant interaction of age with Form versus Motion Condition 1, $F(4, 130) = 0.4$, $p > .70$, $\eta_p^2 = .01$. A one-tailed Dunnett's analysis of the effect of age on form thresholds revealed that 3-year-olds' mean threshold was worse than adults' mean threshold ($p < .01$) while thresholds for 5-, 7- and 10-year-olds were no different than those of adults (*ps* > .05). Here, the significant main effect of condition indicates that form thresholds were better than motion thresholds. We found the same pattern of results when the Form Condition was compared to Motion Condition 2. There were significant main effects of age and condition, $F(4, 130) = 19.6$, $p < .001$, $\eta_p^2 = .38$ and $F(1, 130) = 112.0$, $p < .001$, $\eta_p^2 = .46$, respectively, but no significant interaction $F(4, 130) = 0.8$, $p = .52$, $\eta_p^2 = .02$.

Linear Regression analyses revealed that there was a significant linear relationship between log age and log modulation depth threshold for first-order stimuli, $F(1, 278) = 60.4$, $p < .001$, and for second-order stimuli, $F(1, 278) = 73.7$, $p < .001$. There was also a significant linear relationship between log age and log modulation depth threshold for every first- and second-order condition analyzed separately (*ps* < .005). Across all conditions, the slope for first-order stimuli was steeper than that for second-order stimuli, $\beta = -.57$, $p < .001$, $\beta = -.26$, $p < .001$, respectively. Slope coefficients were also larger for first-order than second-order stimuli in every condition tested (all *ps* < .001). The steeper slopes indicate that there was more change with age for first-order than for second-order stimuli.

To examine further the differences between first- and second-order developmental trajectories, we compared the mean log threshold for each condition between children at each age and adults. This comparison was done by subtracting the logged thresholds to get the number of log units that children were worse than adults. Threshold elevation scores for first- and second-order

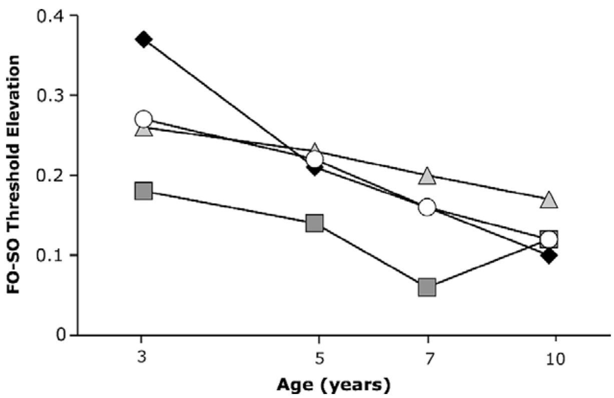

Fig. 3. Children's threshold elevation scores plotted as a function of age. Immaturities for first-order (FO) and second-order stimuli (SO) were calculated by subtracting children's mean log threshold from adults' mean log threshold for each condition and age group tested. Differences between first- and second-order immaturities (FO – SO) are plotted as threshold elevation scores. Symbols represent various combinations of temporal frequency, spatial frequency, and velocity as in Fig. 2. The threshold elevation scores are all positive, indicating that children are more immature for first-order than second-order stimuli, especially at 3 years of age.

stimuli with the same stimulus values were then subtracted to yield an index of relative immaturity. As shown in Fig. 3, subtracted threshold elevation scores were positive, regardless of condition. This indicates that children's thresholds were elevated above adults' thresholds more for first-order that second-order stimuli, regardless of condition.

4. Discussion

The current study had three main goals: (1) to determine and compare the developmental trajectories of sensitivity to the direction of first-order and second-order motion; (2) to examine the effects of temporal frequency, spatial-frequency, and velocity on sensitivity to first-order and second-order motion; and (3) to examine if sensitivity to motion in children is limited by poor sensitivity to form. To accomplish these goals, we measured sensitivity to first-order and second-order motion and form in adults and compared it to that of children at four different ages.

We found that adults were extremely sensitive to first-order motion, requiring only about 0.3–0.8% luminance modulation to discriminate the direction of a drifting first-order grating. In comparison, adults required around 20–35% contrast-modulation to discriminate the direction of a second-order grating. Although the relative differences between adults' first- and second-order thresholds varies across studies and are sometimes less than found here (e.g., Ledgeway & Smith, 1994b; Smith, Hess, & Baker, 1994), our results show patterns similar to those reported by Ledgeway and Hutchinson (2005) for conditions with spatial and temporal frequencies similar to ours.

We also found that children's thresholds were higher than those of adults, at least at some ages, both for first-order and second-order stimuli. Non-visual factors, such as differences between children and adults in motivation or in ability to pay attention, likely contributed to the difference in thresholds between children and adults. However, non-visual factors are unlikely to be the only explanation of the age differences. Non-visual factors cannot account for the fact that children reached adult-like levels of sensitivity to motion at different ages for different conditions and for the two motion types. For example, children were adult-like by 7 years for all second-order motion conditions, but were immature even at age 10 for first-order motion. Similarly, thresholds for second-order form were adult-like by 5 years of age, whereas they were adult-like for first-order form only at age 10.

4.1. Developmental trajectory for motion

The results indicate that visual immaturities are greater for first-order than second-order motion and that second-order mechanisms reach adult-like thresholds before first-order mechanisms. For first-order motion, children were still immature at age 10. For all second-order motion conditions, children were adult-like by 7 years of age. Furthermore, at younger ages, children's thresholds were elevated above adults' thresholds more for first-order motion than for second-order motion (Fig. 3). Similarly, linear regression analyses revealed steeper slopes for first- than second-order thresholds when regressed on log age. Together, the results suggest that first-order mechanisms undergo more maturation than second-order mechanisms during childhood.

Like us, Bertone et al. (2008) found that children reached adult-like thresholds for second-order before first-order motion. However, unlike us, they reported that 5- to 6-year-olds were more immature for second-order than first-order motion. In contrast, we found that, regardless of age, children were more immature for first-order than second-order motion. One explanation we can offer to account for these discrepancies is that threshold elevations in the Bertone et al. (2008) study were calculated differently than in the present study. Bertone et al. calculated how many times worse children's thresholds were compared to adults' by *dividing* logged thresholds. Log scores cannot be divided meaningfully. The comparison must be done either by dividing unlogged thresholds to get a ratio of 'times worse' than adults, or by *subtracting* the logged thresholds to get the number of log units worse than adults. When we recalculated how many times worse children's thresholds were compared to adults' thresholds we found that the 5- to 6-year-olds tested by Bertone et al. were 0.52 log units (3.3 times) worse than adults for first-order motion, and only 0.42 log units (2.6 times) worse than adults for second-order motion. Thus, results from the study by Bertone et al. are in agreement with our findings that children's immaturity is larger for second-order than first-order motion when the analyses are conducted in the same way.

A re-analysis of Ellemberg, Lewis et al. (2003) using the analyses described in the current paper indicates that, as in current findings, 5-year-old children in that study were more immature for first-order than second-order motion, at least when temporal frequency was relatively low. Specifically when temporal frequency and velocity were 1.5 Hz and 1.5 deg/s, respectively, 5-year-olds were only 0.14 log units (1.4 times) worse than adults for second-order motion but 0.38 (2.4 times) worse than adults for first-order motion. When temporal frequency and velocity were 6 Hz and 6 deg/s, respectively, the recalculation shows that 5-year-olds were 0.41 log units (2.6 times) worse than adults for both first-order and second-order motion.

In summary, when immaturities are calculated in the same way, all three studies (Bertone et al., 2008; Ellemberg, Lewis et al., 2003; the current study) agree that, at least at some temporal frequencies, sensitivity to second-order motion is closer to, or reaches, adult levels during childhood more quickly than does sensitivity to first-order motion. Kiorpes, Gavlin, and El-Shamayleh (2006) found a similar pattern of results in monkeys. Specifically, monkeys' modulation sensitivity when discriminating horizontal from vertical texture (a second-order task) was adult-like by 20 weeks of age, while their modulation sensitivity for discriminating luminance-defined horizontal from vertical gratings (a first-order task) did not reach adult-like levels until the monkeys were 40 weeks of age (Kiorpes et al., 2006).

The finding that adult-like sensitivity to second-order motion develops more quickly than adult-like sensitivity to first-order seems paradoxical given filter-rectify filter models in which second-order mechanisms include additional processing stages beyond what is required for first-order mechanisms (Wilson, Ferrera, & Yo, 1992). Bertone et al. (2008) explained the earlier maturity of sensitivity to second-order motion by noting that, in adults, second-order mechanisms are less efficient than first-order mechanisms (Allen, Ledgeway, & Hess, 2004) and hence may require less development to reach mature sensitivity. Other evidence supports this hypothesis. Specifically, second-order motion mechanisms in adults are less directionally selective than first-order motion mechanisms (Ledgeway & Hess, 2002), and human observers are less efficient at detecting contrast-modulations than luminance-modulations compared to an ideal observer (Manahilov, Simpson, & Calvert, 2005). If second-order mechanisms are less efficient or less sensitive than first-order mechanisms, less neural development may be required to reach adult-like levels of second-order processing than first-order processing (Bertone et al., 2008). The lesser efficiency may also make them more vulnerable to insult, as is in the case of amblyopia (Thibault et al., 2007).

Regardless of the specific mechanisms, there is mounting evidence that, at least under some conditions, sensitivity to second-order information reaches adult-like levels before sensitivity to first-order information, both in infant monkeys, and human children (re-analysis of Bertone et al., 2008 and of Ellemberg Lewis et al., 2003; Kiorpes et al., 2006; the current study). These surprising but consistent findings contrast with the pattern reported by Thibault et al. (2007) who reported that sensitivity to first- and second-order motion mature at equal rates. We suspect that the difference in findings is related directly to differences in the tasks. We used a direction discrimination task, which necessarily involves the directional motion system. In contrast, the motion detection task used by Thibault et al. could just as easily reflect sensitivity to flicker or form rather than sensitivity to motion. This is because looking preferences can result from any perceived differences between the test and control stimulus. In the case of Thibault and colleagues, the test stimulus differed from the control stimulus in form (stripes versus grey-scale noise), flicker (generated by the drifting grating but not the static noise), and motion (present versus absent). Thus, the preferences may have been based on any one or combination of these differences. The current study eliminates these confounds by using stimuli that differ only in direction of motion. Furthermore, examination of Fig. 4 in Thibault et al. (2007) indicates that the typically developing controls tested outside the vision clinic had second-order thresholds that were relatively constant after 30 months of age, while their first-order thresholds continued to improve. These data suggest that sensitivity to second-order information asymptotes before sensitivity to first-order information.

4.2. Effects of temporal frequency, spatial frequency, and velocity

Our second goal was to determine what parameters limit sensitivity to motion. Thresholds for first-order motion were similar in the two conditions that had a temporal frequency of 1.5 Hz, despite large differences in spatial frequency and velocity between those two conditions. Thresholds were better for the condition with the higher temporal frequency (6 Hz) rather than the lower temporal frequency (1.5 Hz). The pattern of results differed for second-order motion. Second-order motion thresholds were similar when spatial frequency was 1 cyc/deg, despite very different temporal frequencies and velocities in the two conditions. Thresholds were better when spatial frequency was reduced from 1 cyc/deg to 0.25 cyc/deg, that is, sensitivity to second-order motion increased as spatial-frequency decreased. These patterns were evident at every age from 3 years to adulthood, a result indicating that the basic tuning of first-order and second-order mechanisms is adult-like by 3 years of age.

Our findings that thresholds for first-order motion seem to depend more on temporal frequency whereas thresholds for second-order motion seem to depend more on spatial frequency are consistent with the idea first-order motion is process using motion-sensitive mechanisms, while second-order motion is processed using a feature tracking mechanisms (Seiffert & Cavanagh, 1998, 1999). However, given the small range of values tested, this pattern of results may simply reflect different tuning properties of motion sensitive first- and second-order mechanisms as modeled by Wilson and colleagues (1992). Nonetheless, the fact that the factors limiting sensitivity appear to be similar across age imply that the neural mechanisms underlying the processing of first- and second-order motion have already differentiated by 3 years of age and that subsequent development involves only a quantitative change in their sensitivity.

4.3. Form versus motion

The pattern of results for the form discrimination tasks was similar to that obtained for the motion tasks, with the exception that adult-like thresholds were found at earlier ages in the form task. As with the faster development for second-order than first-order motion, children were already adult-like at 5 years of age for second-order form but did not reach adult-like thresholds until 10 years of age for first-order form. As with motion, younger children's thresholds were more elevated above adults' thresholds for first-order than second-order form and regression analysis showed that first-order thresholds decreased more with age than did second-order thresholds. As discussed previously, relatively faster maturation of sensitivity for second-order than first-order information has been reported for infant monkeys (Kiorpes et al., 2006) and for children (Bertone et al., 2008) tested with similar behavioural tasks.

The results for form indicate that children's immature thresholds for motion cannot be attributed solely to poor sensitivity to the form carrying the motion signal. Specifically, children reached adult-like thresholds for both first- and second-order form before motion, and first-order motion thresholds were *better* than form thresholds at every age tested. The faster development of sensitivity to form than sensitivity to motion is consistent with findings that infants show a significant visual evoked potential (VEP) response to orientation reversals at an earlier age than they show a significant VEP response to directional reversals (Braddick, Birtles, Wattam-Bell, & Atkinson, 2005).

We also compared the pattern of results for form and motion across first-order and second-order stimuli. In all groups, thresholds for first-order motion discrimination were lower than for first-order horizontal/vertical discrimination. However, the opposite result was obtained with second-order stimuli: horizontal/vertical discrimination thresholds were lower than motion discrimination thresholds. More simply, we can discriminate the direction of first-order motion even if we cannot see its form. However, we can discriminate the direction of second-order motion *only if* we can see its form. Others have also found that adults' second-order motion thresholds are worse than their second-order orientation identification thresholds and have used this finding as confirmation that the second-order motion stimuli do not contain first-order artifacts (Ledgeway & Hess, 2002).

In summary, we found differences in the pattern of results for first-order and second-order motion and form. Sensitivity to second-order motion and second-order form reach adult-like levels before sensitivity to first-order motion and first-order form; and younger children's thresholds are more immature for first-order than second-order stimuli. This is likely related to the fact that adults are relatively insensitive to second-order stimuli (Allen et al., 2004; Ledgeway & Hess, 2002). Thus, reaching adult-like levels of sensitivity to second-order stimuli likely requires less developmental refinement than is the case for first-order motion. When stimuli are first-order, observers are more sensitive to motion than form and their sensitivity varies with temporal frequency. When stimuli are second-order, observers are more sensitive to form than motion and sensitivity varies with spatial frequency. These patterns are evident by 3 years of age, the youngest age tested. Overall, these results support that idea that there are differences in the mechanisms that process first-order and second-order motion and that these mechanisms develop at different rates.

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