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Discrimination of speed in 5-year-olds and adults: Are children up to speed?

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Abstract

We compared thresholds for discriminating changes in speed by 5-year-olds and adults for two reference speeds: 1.5 and 6° s^{-1}. Both adults and 5-year-olds were more sensitive to changes from the faster than from the slower reference speed. Five-year-olds were less sensitive than adults at both reference speeds but significantly more immature at the slower (1.5° s^{-1}) than at the faster (6° s^{-1}) reference speed. The findings suggest that the mechanisms underlying speed discrimination are immature in 5-year-olds, especially those that process slower speeds.

Keywords: Visual development; Speed discrimination; Children; Adults

1. Introduction

Studies of monkeys indicate that area MT plays a critical role in processing speed (Perrone & Thiele, 2002). More than 90% of neurons within area MT are tuned narrowly to speed and organized in clusters based on preferred speed (Liu & Newsome, 2003). Of these neurons, 7–9% are low-pass (respond preferentially to speeds less than about 2° s^{-1}), 15–21% are high-pass (respond preferentially to speeds greater than about 20–60° s^{-1}), and the majority respond preferentially to a narrow band of intermediate speeds (Liu & Newsome, 2003). Moreover, these speed-tuned neurons appear to operate independently of spatial and temporal frequency because their firing rate is affected very little by random variations in spatial and temporal frequency (Perrone & Thiele, 2002).

Neuro-imaging studies of humans using fMRI and PET indicate that an area analogous to monkey MT is involved in speed processing. For example, there is greater activation in the human MT complex when adults are asked to discriminate speed than when they are asked to discriminate colour, shape, luminance, or contrast (Beauchamp, Cox, & DeYoe, 1997; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Huk & Heeger, 2000). Moreover, when adults discriminate speed, there is more activation of the MT complex than of the primary visual cortex or any other areas along the extrastriate dorsal stream (Huk & Heeger, 2000).

The neural mechanisms underlying the calculation of speed are computationally more complex than those coding direction. Churchland and Lisberger (2001) propose that speed is estimated from the MT population response by a computation that implements a vector

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average based on opponent motion. For a typical vector average, the response of every neuron is multiplied by a vector pointing in its preferred direction with length proportional to its preferred speed. These vectors are then summed and normalized by the total activity. However, an opponent motion vector average considers only neurons with preferred directions oriented with, or opposite to, the direction of stimulus motion. The vector average thus yields a single scalar that gives an estimate of the speed of the stimulus (Churchland & Lisberger, 2001). This neural mechanism allows not only the computation of speed, but also the discrimination of speed, because it allows for comparisons between individual estimates of stimulus speed.

As predicted from animal models, human adults can discriminate small differences in speed. Speed discrimination is typically better when the reference speed is faster than $2° s^{-1}$ than when it is slower (Bravo & Watamaniuk, 1995; Gibson, Smith, Steinschneider, & Johnson, 1957; Johnston, Benton, & Morgan, 1999; McKee, 1981; McKee, Silverman, & Nakayama, 1986). For example, McKee et al. (1986) asked subjects to judge whether a grating was moving faster or slower than an implicit reference speed. Adults needed a 5% difference in speed to discriminate targets moving faster than $2° s^{-1}$ but a 10% difference for targets moving slower than $2° s^{-1}$. Moreover, as in monkey MT, psychophysical data from humans indicates that sensitivity to speed is independent of spatial and temporal frequency: random variations in spatial and temporal frequency have little effect (McKee et al., 1986); cross-adaptation and cross-masking between velocity mechanisms and spatial and temporal frequency mechanisms do not occur (Reisbeck & Gegenfurtner, 1999; Schrater & Simoncelli, 1998), and temporal frequency discriminations are affected little by random variations in velocity (Smith & Edgar, 1991).

Little is known about the development of speed discrimination, other than studies showing that infants can discriminate a moving from a stationary target (Aslin & Shea, 1990; Volkmann & Dobson, 1976). Although these studies varied in the stimuli used and threshold criteria, they agree that, until at least 6 months of age, sensitivity to stimuli moving at slower speeds is more immature than sensitivity to stimuli moving at faster speeds (Aslin & Shea, 1990; Volkmann & Dobson, 1976). For example, when discriminating a stationary from a moving grating, 6-week-olds show no evidence of discriminating between stationary targets and ones moving slower than $9° s^{-1}$. Similarly, 12-week-olds show no evidence of discrimination for targets moving slower than $4° s^{-1}$ (Aslin & Shea, 1990).

Although there have been no studies of speed perception beyond infancy, we expected that even 5-year-olds would be immature at discriminating speed based on their immaturities in other aspects of motion perception. For example, compared to adults, 5-year-olds need significantly more contrast in sinusoidal gratings to detect motion (Armstrong, Lewis, Ellemberg, Bhagirath, & Maurer, 2004) and to discriminate the direction of motion (Ellemberg et al., 2003). On a global motion task which, like speed discrimination, requires integration of local motion signals by the MT complex, 5-year-olds require a much greater percentage of drifting gabors to move coherently in order to gage the direction of global motion than do adults, especially when the drift rate is slow ($1.5° s^{-1}$) (Ellemberg et al., 2004; see also Gunn et al., 2002).

The purpose of the present study was to compare thresholds for discriminating speed in 5-year-olds and adults. We began our developmental studies with 5-year-olds because we have found that children of this age can produce reliable psychophysical thresholds (Ellemberg et al., 2003, 2004; Ellemberg, Lewis, Liu, & Maurer, 1999). In the present study, subjects were shown, sequentially, two moving gratings and had to decide which one was moving faster. Half the subjects were tested with a reference speed of $1.5° s^{-1}$ and half with a reference speed of $6° s^{-1}$. The stimulus parameters were chosen to match those in our previous studies of sensitivity to the direction of first-order local motion (Ellemberg et al., 2003).

2. Methods

2.1. Subjects

The subjects were two groups of 24 adults (mean age = 19.8 years, range 17.9–27.8 years) and two groups of 24 children who were 5 years of age ± 3 months (mean age = 5.1 years, range 4.8–5.2 years). None of the subjects had a history of eye problems, and all met our criteria on a visual screening examination. Specifically, adults had a linear letter acuity (Lighthouse visual acuity chart) of at least 20/20 in each eye without optical correction, worse acuity with a +3 dioptre add (to rule out hypermetropia of greater than 3 dioptres), fusion at near on the Worth four dot test, and stereoacuity of at least 40″ on the Titmus test. The 5-year-olds met the same criteria except that they were required to have a visual acuity of at least 20/25 when tested with the Good-lite Crowding cards. We relaxed the criteria for children because letter acuity is still immature at 5 years of age (Simons, 1983; reviewed in Maurer & Lewis, 2001). For the test of acuity, children were shown flash cards (Good-lite, catalogue # 1010), each of which contained one letter (H, O, T, or V) flanked by six comparably sized vertical bars to the left and to the right. The smallest letter that children identified (by pointing to the match on a hand-held card) provided a measure of visual acuity. An additional 12 adults and 2 children were eliminated from the final sample because they failed to meet our criteria on the visual screening exam.

2.2. Apparatus and stimuli

The stimuli were generated by a Macintosh G3 computer by means of VPixx 1.64 software™, and were displayed on a Sony Trinitron Multiscan 200 gs monitor, 35° wide × 27° high when viewed from a distance of 50 cm. The monitor had a frame rate of 75 Hz and a pixel resolution of 1024 × 768.

The stimuli consisted of 1 c deg^{-1} horizontal sinusoidal gratings, 10° wide × 10° high, identical to the first-order stimuli described by Ellemberg et al. (2003, 2004). Briefly, luminance-modulated gratings were added to static random noise composed of 2 × 2′ black-and-white elements. This appeared like a conventional luminance-modulated sinusoidal grating. The stimuli drifted upwards for 1000 ms at one of two reference speeds (1.5 or 6° s^{-1}) and various comparison speeds.

2.3. Procedure

The procedures were explained and informed consent was obtained from the adults and from parents of the 5-year-olds. The experimental protocol was approved by the McMaster Research Ethics Board. Subjects were tested binocularly in a room illuminated only by the computer monitor and were adapted to the lighting conditions prior to the test. The subject was seated 50 cm from the stimuli with the chin positioned on a chin-rest. Parents sat in the testing room out of their child's sight and were asked to remain silent throughout the testing.

Subjects were instructed to fixate a target in the centre of the screen that appeared between trials. On each trial, subjects were shown two moving gratings sequentially, each for 1000 ms, separated by a 500 ms interstimulus interval. Subjects were asked to judge which of the two gratings was moving faster. The experimenter said: "You will see a box with moving stripes. It will disappear and then you will see another box with moving stripes. Your job is to tell me which of the boxes had stripes that were moving faster, box number one, or box number two." The experimenter pressed a key to begin a trial and entered the responses by means of the keyboard. The experimenter also watched the participant's eyes continuously to ensure that he/she was looking at the centre of the screen, provided regular reminders to do so, and began a trial only when the participant was looking in the middle of the screen. Half the subjects at each age were tested with the reference speed of 1.5° s^{-1} and the other half with the reference speed of 6° s^{-1}. We used a two-alternative temporal forced choice procedure in which the faster comparison velocity appeared randomly in interval 1 or interval 2. The procedure began with a demonstration, criterion trials, and a practice run.

2.3.1. Demonstration trials

The demonstration consisted of two trials. The first trial consisted of one stimulus moving at the assigned reference speed (1.5 or 6° s^{-1}) and a comparison stimulus moving at a fixed speed (7° s^{-1} for a reference speed of 1.5° s^{-1} or 18° s^{-1} for a reference speed of 6° s^{-1}). The second trial was identical except that the order of presentation was reversed. For each demonstration trial, the experimenter asked the participant to choose which stimulus (the first or second) was moving faster and provided verbal feedback.

2.3.2. Criterion trials

The purpose of the criterion was to verify that subjects understood the task. Subjects were presented with a block of four trials, each of which had the same reference speed (1.5 or 6° s^{-1}) and comparison speed (7 or 18° s^{-1}) as the demonstration trials. During the block of four trials, the reference speed appeared twice in the first interval and twice in the second interval, with the four trials presented in a random order. To be included in the study, participants had to judge correctly which box had faster moving stripes ("one" or "two") on all four trials within a block. Subjects had three chances to meet this criterion and all subjects did so within two tries.

2.3.3. Practice run

Thresholds were calculated using a maximum-likelihood threshold estimation procedure (ML-TEST) in which the value of the dependent variable that is presented on each trial is the best estimate of the subject's threshold based on the history of the run (Harvey, 1986). Threshold was defined as the minimum speed needed to discriminate accurately a comparison speed from a reference speed of 1.5 or 6° s^{-1}. Specifically, each measurement of threshold was stopped at the value corresponding to 82% correct responses with a confidence interval of 95% that the estimate was accurate within ±0.1 log units. Each subject was given a full practice staircase. The experimenter was aware of the stimulus presented during each interval and if the subject began making mistakes on "easy" trials, provided feedback and encouragement.

2.3.4. Test of thresholds

The procedure for measuring each threshold was identical to that for the practice run, except that the experimenter was unaware of the stimulus presented during each interval and provided encouragement but no feedback. Subjects were given as many breaks as necessary and all subjects completed the testing protocol in one session that lasted no more than 1 h. The mean number of trials to measure each threshold was 66 (range = 27–129) for children and 69 (range = 47–126) for adults.

2.4. Pilot studies to equate the visibility of the two reference speeds

To equate visibility, the luminance contrast of the stimuli was set for each reference speed and age group to four times the threshold we had found in a previous study for detecting the direction of motion of the same stimulus (Ellemberg et al., 2003). We then verified that those values were optimal by showing that performance did not improve when the contrast was increased from four times the direction discrimination threshold to five and six times threshold. These pilot studies were conducted with four adults (18.9–19.7 years) and four 5-year-olds (±3 months). Two subjects of each age performed the speed discrimination task for all three contrast levels at each reference speed. The pilot work showed that at both ages and at both reference speeds, subjects' performance was consistent whether the contrast was set at four times the direction discrimination threshold, or at five or six times threshold. This indicates that subjects would not have performed better had we chosen higher values. Thus the contrast values for each condition and age were set at four times the direction discrimination threshold for that condition and age: 0.04 and 0.02 for adults, and 0.13 and 0.09 for children tested at 1.5 and $6° s^{-1}$, respectively. The mean luminance for each of these conditions was 27.8, 27.7, 28.2 and 26.3 cd/m^2, respectively.

2.5. Data analysis

The original data set consisted of one threshold for each individual in each of two groups of adults and two groups of 5-year-olds, each tested at one of two reference speeds (1.5 or $6° s^{-1}$). An outlier procedure recommended by Kirk (1989) was used to replace deviant scores. Specifically, each threshold was converted to a *z*-score using the mean and standard deviation for that age and reference speed. *Z*-scores greater than +2.5 or less than −2.5 were replaced with the original group mean (i.e., the mean threshold for the condition before the removal of outliers). Four data points were replaced, one from adults tested with a reference speed of $1.5° s^{-1}$ and three from 5-year-olds (one tested with a reference speed of $1.5° s^{-1}$ and two tested with a reference speed of $6° s^{-1}$). All subsequent analyses were conducted using this revised data set.

We began by converting each individual threshold from the raw value to a Weber fraction, namely the proportion by which the comparison stimulus had to move faster than the reference stimulus for accurate discrimination 82% of the time. To do so we used the formula:

$$\text{Proportion increase} = (\text{raw threshold} - \text{reference speed})/\text{reference speed}$$

We conducted one two-way ANOVA, with two between-subjects variables (age and speed). There were two levels of age (5-year-old and adult) and two levels of speed (1.5 and $6° s^{-1}$). Any significant interaction was investigated with analyses of simple effects. As is customary in the literature on speed discrimination (e.g., Bravo & Watamaniuk, 1995; Mateef et al., 2000; McKee, 1981; McKee et al., 1986), we used those Weber fractions untransformed in the data analyses and plotted the results on a linear scale.

3. Results

As shown in Fig. 1, adults performed better than 5-year-olds at both reference speeds. At the slower reference speed ($1.5° s^{-1}$), adults required a 37% increase in speed for accurate discrimination whereas 5-year-olds needed a 108% increase. At the faster reference speed ($6° s^{-1}$), adults required a 13% increase in speed for accurate discrimination whereas 5-year-olds needed a 44% increase. The ANOVA on these values revealed a significant interaction between age and reference speed ($F_{1,92} = 5.844$, $p < 0.0176$) as well as main effects of age and speed (*p*s < 0.0001). The post-hoc analysis on the interaction revealed that 5-year-olds had significantly higher thresholds than adults at both reference speeds ($p < 0.0001$), but were significantly more immature at the slower than at the faster reference speed ($p < 0.0001$). As shown in Fig. 1, both age groups had higher thresholds at the slower reference speed.

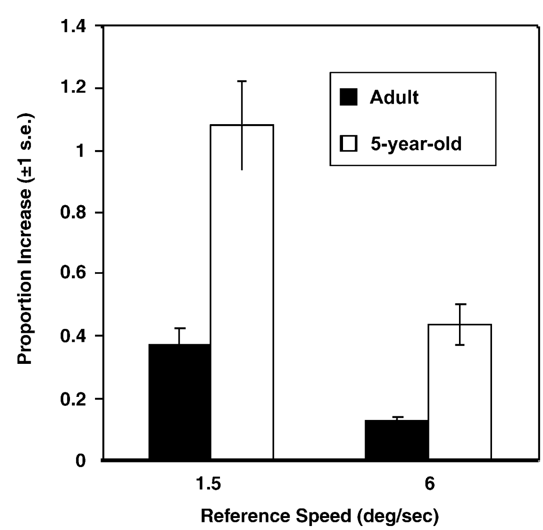

Fig. 1. The proportion by which the comparison stimulus had to move faster than the reference stimulus for accurate discrimination 82% of the time. Black bars represent the mean thresholds (±1 s.e.) for the adults and white bars represent the mean thresholds (±1 s.e.) for the 5-year-olds.

4. Discussion

Our findings indicate that the mechanisms underlying speed discrimination are immature in 5-year-olds: children needed a larger increase in speed than did adults for accurate discrimination. This was true both at the slower (1.5° s^{-1}) and at the faster (6° s^{-1}) reference speeds. However, the difference in performance between 5-year-olds and adults was significantly larger at the slower than at the faster reference speed. Thus, in children, the mechanisms underlying speed discrimination are especially immature at slower speeds.

Although non-visual factors, such as differences between the 5-year-olds and adults in attention or response biases, may have contributed to the differences in threshold, they cannot account for the fact that 5-year-olds are more immature at the slower speed. All tasks measured thresholds; yet the difference between the thresholds of 5-year-olds and adults was much larger for the slower than for the faster reference speed. Nor is it likely that adaptation effects caused by the consistent upward direction of motion are the explanation for differences in thresholds between 5-year-olds and adults. It is true that adaptation effects on our measure of speed discrimination would have led to improved discrimination as adaptation time increased (Clifford & Wenderoth, 1999; Kristjansson, 2001), moreso for the faster than the slower speed (Hammett, Thompson, & Bedingham, 2000; Hoffmann, Dorn, & Bach, 1999), and moreso for adults than children (Harris, 1983). However, any adaptation effects should saturate long before the end of the staircase procedure (Hammett et al., 2000). In fact, an analysis of variance comparing estimated thresholds on the 20th versus the final trial revealed no systematic improvement in performance over time at either speed for either children or adults.

One could argue that, because stimuli were presented for constant intervals of 1000 ms, subjects might have used a fixation mechanism (counted and compared the number of stripes moving past a certain point in the stimulus interval) to determine which set of stripes was moving faster. Five-year-olds might be less accurate than adults in using such a counting strategy, or less likely to use it. However, had subjects used such a strategy, thresholds would have been worse for the faster moving stripes that are harder to count than for the slower moving stripes—exactly the opposite from what we found for both adults and 5-year-olds.

The results of the present study are akin to those for the detection of motion during early infancy (Aslin & Shea, 1990), as even infants show better performance for faster speeds than for slower speeds. Specifically, when tested on their ability to detect motion, 6- and 12-week-olds show no evidence of discriminating between stationary targets and ones moving slower than 9° s^{-1} and 4° s^{-1}, respectively (Aslin & Shea, 1990). Infants' especially poor sensitivity at slower speeds has been attributed to their poor spatial resolution and especially poor contrast sensitivity at low temporal frequencies (Freedland & Dannelmiller, 1987; Kaufmann, 1995; Roessler & Dannemiller, 1997). A similar pattern is seen in sensitivity to the direction of global motion in drifting gabors: 5-year-olds' coherence thresholds are immature at all speeds, but the difference is far larger for 1.5° s^{-1} than for 6 and 9° s^{-1} (Ellemberg et al., 2004).

However, the pattern of results for speed discrimination and global direction of motion at 5 years of age is very different from that for motion detection and for the discrimination of direction of local motion. Specifically, whereas speed discrimination is worse for a reference speed of 1.5° s^{-1} than for a reference speed of 6° s^{-1}, the minimum contrast necessary to detect motion in similar stimuli is equally good at the two speeds (Armstrong et al., 2004), as is the ability to discriminate whether stripes are moving up or down (Ellemberg et al., 2003). This indicates that patterns of development do not necessarily generalize across different aspects of motion processing and may differ systematically for local motion and for aspects of motion like global direction and speed that require additional processing in the MT complex.

In the current study, both children and adults were worse at discriminating speed at the slower (1.5° s^{-1}) than at the faster (6° s^{-1}) reference speed, a pattern similar to that of previous studies (Mateef et al., 2000; McKee, 1981; McKee et al., 1986; Shallo-Hoffmann, Bronstein, Acheson, Morland, & Gresty, 1998). Adults in the current study needed a 13% difference in speed to discriminate a target from a reference speed of 6° s^{-1}, and a 37% difference for accurate discrimination if the reference speed was 1.5° s^{-1}. This performance is worse than that reported in previous studies showing that adults need only a 5–6% difference in speed to discriminate a target from a reference speed of at least 2° s^{-1} (Bravo & Watamaniuk, 1995; Gibson et al., 1957; Johnston et al., 1999; McKee, 1981; McKee et al., 1986) and only a 10% difference to accurately discriminate speeds slower than 2° s^{-1} (McKee et al., 1986). This discrepancy is unlikely to be caused by our subjects' adapting to the consistent upward direction of the stripes because adaptation *improves* speed discrimination (Clifford & Wenderoth, 1999; Kristjansson, 2001). A more likely explanation is that, unlike previous studies, our stimulus had noise added, which reduces sensitivity (Pelli & Farell, 1999; Simpson, Falkenberg, & Manahilov, 2003). Nevertheless, there is agreement across studies of poorer sensitivity to differences in velocity at speeds below 2° s^{-1}. Note, that although the difference between 5-year-olds and adults was greater for the slower reference speed, in some respects changes in the reference speed had the same effect at the two ages: both ages required a 3-fold larger difference in speed to see a change from $1.5^\circ\,s^{-1}$ than from $6^\circ\,s^{-1}$ (37 versus 13% for adults; 108 versus 44% for 5-year-olds). Studies at other ages are necessary to ascertain whether this ratio remains constant during development, in which case the linear changes in the Weber fraction would have to change more rapidly for the slower than the faster speed.

Under the present testing conditions, we cannot determine whether the pattern of results for the slower versus faster speed is a consequence of differences in sensitivity to speed or to temporal frequency. We kept spatial frequency constant at $1\,c\,deg^{-1}$. Thus, temporal frequency varied directly with speed: 1.5 and 6 Hz for the slower ($1.5^\circ\,s^{1}$) and faster speeds ($6^\circ\,s^{-1}$), respectively. However, studies with adults indicate that, within the range of temporal frequencies used in the current study, speed discrimination thresholds are affected little by large random changes in spatial frequency, and hence affected little by the temporal frequency of the pattern to be discriminated (McKee et al., 1986).

The present finding of poorer speed discrimination in 5-year-olds than adults might be attributable either to immaturities of the neural mechanisms underlying speed processing per se (area MT) or of the lower cortical levels involved in spatial and temporal coding. One possibility is that children are immature at discrimination both for slower and faster reference speeds because neurons within area MT are less sharply tuned to speed in children than in adults. These neuronal immaturities might have a greater effect on the discrimination of slower than faster speeds because so few neurons are tuned to slow speeds, at least in adult monkeys (Liu & Newsome, 2003). Alternatively, or in addition, the limitation might be at the level of the initial filters. Speed discrimination involves the integration of temporal and spatial frequency coded in lower cortical areas (Perrone & Thiele, 2002). Perhaps it is immaturities in temporal contrast sensitivity at low temporal frequencies that underlie greater immaturities for the discrimination of slower than faster speeds: visually normal 5-year-olds are less sensitive than adults at low, but not at high, temporal frequencies (Ellemberg, Lewis, Liu, et al., 1999). Consistent with this hypothesis are findings that visually normal infants and patients treated for congenital cataract also have relatively poor sensitivity at lower temporal frequencies and have relatively poor motion processing at slow speeds (Ellemberg, Lewis, Maurer, & Brent, 2000; Ellemberg, Lewis, Maurer, Lui, & Brent, 1999).

In summary, we found a different developmental pattern for sensitivity to slower versus faster speeds. Both children and adults are less sensitive to changes in speed for the slower ($1.5^\circ\,s^{-1}$) than for the faster ($6^\circ\,s^{-1}$) reference speed. Though 5-year-olds are less sensitive than adults for changes from both reference speeds, they are especially immature at the slower speed ($1.5^\circ\,s^{-1}$). These results imply that the mechanisms underlying speed discrimination mature after 5 years of age. They also indicate that the mechanisms used to process slower speeds develop less rapidly than those used to process faster speeds. Thus, in the real world, children likely have more difficulty discriminating the speed of slowly moving objects than those moving more quickly.

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