

The development of global motion discrimination in school aged children

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Global motion perception matures during childhood and involves the detection of local directional signals that are integrated across space. We examine the maturation of local directional selectivity and global motion integration with an equivalent noise paradigm applied to direction discrimination. One hundred and three observers (6–17 years) identified the global direction of motion in a 2AFC task. The 8° central stimuli consisted of 100 dots of 10% Michelson contrast moving 2.8°/s or 9.8°/s. Local directional selectivity and global sampling efficiency were estimated from direction discrimination thresholds as a function of external directional noise, speed, and age. Direction discrimination thresholds improved gradually until the age of 14 years (linear regression, $p < 0.05$) for both speeds. This improvement was associated with a gradual increase in sampling efficiency (linear regression, $p < 0.05$), with no significant change in internal noise. Direction sensitivity was lower for dots moving at 2.8°/s than at 9.8°/s for all ages (paired t test, $p < 0.05$) and is mainly due to lower sampling efficiency. Global motion perception improves gradually during development and matures by age 14. There was no change in internal noise after the age of 6, suggesting that local direction selectivity is mature by that age. The improvement in global motion perception is underpinned by a steady increase in the efficiency with which direction signals are pooled, suggesting that global motion pooling processes mature for longer and later than local motion processing.

Introduction

The ability to detect movement and to discriminate speed and direction are fundamental visual functions for navigation and safe mobility in an environment that is dynamic in three-dimensions. The visual perception of motion is initially based on the responses of retinotopic motion sensors in primary visual cortex, V1, that are selective for the speed and direction of movement within a relatively small area of the visual field (Hubel & Wiesel, 1962). In order to detect the movement of objects that are larger than V1 receptive fields, local motion signals must be integrated across larger regions of the visual field. The medial temporal area, MT, in primate brains is implicated in the global processing of local motion signals and has been identified in electrophysiological (Zeki, 1974), lesion (Newsome & Pare, 1988), single neuron recording (Liu & Newsome, 2003; Maunsell & Van Essen, 1983), human stroke patient (Zihl, von Cramon, & Mai, 1983), Functional Magnetic Resonance Imaging (Beauchamp, Cox, & DeYoe, 1997; Huk & Heeger, 2000; Tootell et al., 1995), and micro stimulation (Salzman, Murasugi, Britten, & Newsome, 1992) studies. Neurons in MT have receptive fields about 10 times the diameter of those in V1, and are well suited to extract global motion from local motion signals over space and time in order to encode the movements of larger objects (Bruce, Georgeson, & Green, 2003).

Although the literature is inconsistent concerning why the development of motion perception in children takes so long, most studies find that children improve

Citation: Bogfjellmo, L.-G., Bex, P. J. & Falkenberg, H. K. (2014). The development of global motion discrimination in school aged children. *Journal of Vision*, 14(2):19, 1–12, <http://www.journalofvision.org/content/14/2/19>, doi:10.1167/14.2.19.

with development. Global motion perception is believed to mature between the age of 7 and 12 years (Armstrong, Maurer, & Lewis, 2009; Ellemberg, Lewis, Hong Liu, & Maurer, 1999; Gunn et al., 2002; Parrish, 2005). Studies have used random dot kinematograms (RDK) to examine the development of global motion perception by measuring motion coherence thresholds (MCTs) (Manning, Aagten-Murphy, & Pellicano, 2012; Parrish, 2005). MCTs estimate the smallest proportion of signal dots required for direction identification. Sensitivity to complex patterns of global motion, such as expansion and rotation, develop later in childhood (Baumberger & Fluckiger, 2004) and some are not fully developed even in teenagers, depending on the stimulus and parameters that are used (Armstrong et al., 2009; Atkinson, Braddick, & Moar, 1977; Baumberger & Fluckiger, 2004; Ellemberg et al., 2004; Falkenberg, Dutton, & Simpson, 2010; Parrish, Giaschi, Boden, & Dougherty, 2005; Regal, 1981). Very young infants are not able to perform forced choice psychophysical experiments. To study the development of motion perception, several authors have therefore measured involuntary directional eye movements elicited by moving stimuli. With this technique, it has been shown that sensitivity to the direction of moving patterns is present as early as 3 months of age (Dobkins, Fine, Hsueh, & Vitten, 2004) and, when corrected for contrast sensitivity, show little further development into adulthood (Blumenthal, Bosworth, & Dobkins, 2013). The observation that chromatic segmentation cues can improve motion perception without changing directional eye movements suggests that the eye movement response is largely driven by low level motion signals and is unaffected by attentional factors (Dobkins & Sampath, 2008).

In order to determine the global direction of motion of a random dot stimulus, an observer must first detect the *local* direction of motion of one or more of the moving dots and then combine a number of such local direction estimates to estimate the overall direction of *global* motion. The observer's performance at the task is limited by both of these stages; however, the MCT paradigm does not independently quantify either of these stages. It is possible that these two stages may mature at different rates during normal development and that each stage may be differentially affected by impairment of motion perception. The aim of this study is to use an equivalent noise (EN) paradigm (see Appendix for details) to investigate the normal development of sampling efficiency and internal noise using a global direction discrimination task. In the EN paradigm, all dots are signal dots and give information of the total direction of the dot pattern. The EN paradigm measures the influence that additional external noise, the variability of directions added to each dot, has on the ability to recognize the overall global direction of

motion for each observer (Dakin, Mareschal, & Bex, 2005). The advantage of EN is that having two separate measures of sampling efficiency and internal noise allow us to make hypotheses about the maturation of motion mechanisms. Recently, we have shown using the EN paradigm in an aging study, where the observers' age ranged from 20–89 years, that the reduced direction discrimination of global motion with age is due to a decrease in sampling efficiency and an increase in internal noise (Bogfjellmo, Bex, & Falkenberg, 2013). This suggests that the ability to integrate motion signals is reduced in older observers in addition to local motion sensors becoming less selective in their responses to directional signals.

In this study we estimated the development of local direction sensitivity and global direction pooling on global motion discrimination (Bogfjellmo et al., 2013; Dakin et al., 2005) using an EN model in school aged children from 6 to 17 years old. As motion sensitivity is found to develop later for slower than faster speeds (Ahmed et al., 2005; Aslin & Shea, 1990; Banton, Dobkins, & Bertenthal, 2001; Dobkins & Teller, 1996; Manning et al., 2012), we examined internal noise and sampling efficiency for two speeds.

Methods

Observers

One hundred and three naive observers from the ages of 6 to 17 years participated in the study. Observers were recruited from three schools in Mosjen, Norway. Observers were included if they had normal or corrected-to-normal visual acuity of 0.8 Snellen (95 observers had visual acuities better than 1.0), normal contrast sensitivity tested on an iPad (Dorr, Lesmes, Lu, & Bex, 2013), stereo acuity better than 120" and normal visual health. The parents of all observers signed an informed consent form, and the tenets of the Declaration of Helsinki were followed. The study had an ethical approval from the Regional Ethical Committee of Norway.

Apparatus and stimuli

Random dot motion stimuli were generated using MatLab (MathWorks) version R2010a integrating elements of the PsychToolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on a MacBook Pro with a 15-inch Glossy Widescreen LCD Display (refresh rate 60 Hz) with a mean luminance of 91 cd/m². The display was calibrated every day of testing using a Spyder 3 Elite (Datacolor, Lawrenceville, NJ). Each stimulus contained

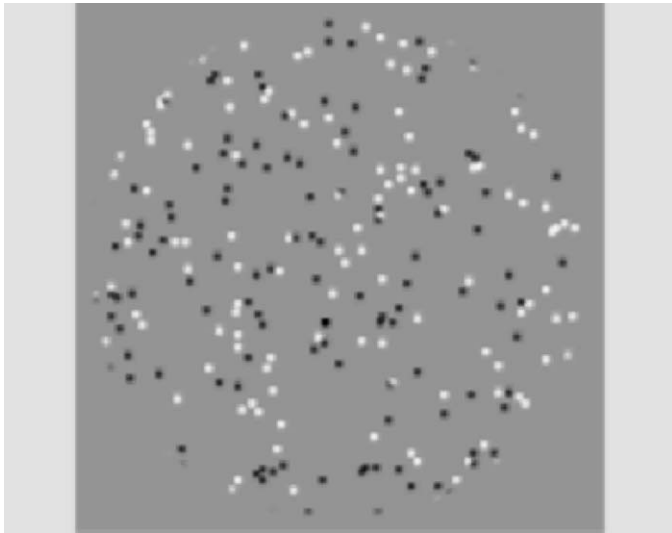


Figure 1. Illustration of a single frame of the stimulus used in the experiments. On each trial, the observer fixated a central colored point and reported whether the global motion of the dots was clockwise or counter-clockwise or upwards.

50 white and 50 black circular dots moving to the right or left of upwards in a circular 8° aperture. The use of dark and light dots prevented any change in mean luminance at the onset and offset of the stimulus. The dot diameter was 6 pixels (0.14°), the dot Michelson contrast was 10%, and the dot speed was $2.8^\circ/\text{s}$ or $9.8^\circ/\text{s}$ (Figure 1), well within the preferred speeds for MT neurons, which are from $2^\circ/\text{s}$ to $256^\circ/\text{s}$ (Maunsell & Van Essen, 1983). A restricted dot lifetime of three frames prevented observers tracking individual dots. Each dot was initialized with a random age to avoid synchronized expiry, and were randomly repositioned in the display aperture at the end of their lifetime. The stimulus duration was 0.5 seconds.

Procedure

In a single interval two alternative forced-choice presentation, observers judged whether the overall direction of motion was clockwise or anticlockwise of upwards while they fixated a central, stationary colored point. Observers were encouraged to guess when not sure of the direction. The observer's response was reported verbally to the examiner (LGB) who pressed the keypad without viewing the stimulus. Feedback was provided by changing the color of the fixation point; green for correct responses, and red for incorrect responses. Before starting the experiment, all observers completed two test runs of 10 trials to ensure that they understood the task. The stimulus was run in a fixed order, where speed $9.8^\circ/\text{s}$ was tested before speed $2.8^\circ/\text{s}$. This was done because we have previously found that

thresholds for the faster speed are lower (Bogfjellmo et al., 2013), and practice with the easier speed condition was helpful. Each observer completed one experiment of 50 trials for each speed. Each test lasted about 3 min, and the whole experiment took about 20 min including breaks. Observers viewed the display binocularly from a head rest at 57 cm in an otherwise dark room.

Equivalent noise analysis

Direction noise was added to all dots to allow for an EN paradigm (Bogfjellmo et al., 2013; Dakin et al., 2005) to be used to estimate internal noise σ_{int} and sampling efficiency N_{samp} for each observer. The EN function (Equation 1) describes direction discrimination threshold as a function of external noise:

$$\sigma_{obs} = \sqrt{\frac{\sigma_{int}^2 + \sigma_{ext}^2}{N_{samp}}} \quad (1)$$

where σ_{obs} is the observed direction discrimination threshold, σ_{int} is internal noise (i.e., the directional uncertainty in the observer's visual system), σ_{ext} is external noise, i.e., the variance of the direction distribution from which dot directions were drawn, and N_{samp} is the number of dots used by the observer to estimate the global direction of all dots. The precision of each dot's direction estimate and the number of integrated dots jointly determine performance. The important assumption of the model is that internal noise is constant. When the external noise is low, performance depends primarily on internal noise. When external noise is high, performance depends primarily on global extraction of information (Dakin et al., 2005). Direction threshold (Figure 2) is the smallest angle required to discriminate the direction of motion on 75% trials without added directional noise (direction standard deviation was 0°).

The EN algorithm was implemented with the FAST toolbox (Vul, Bergsma, & MacLeod, 2010) which selected the direction angle of global motion, and the standard deviation of the direction distribution from which local dot directions were sampled on each trial. The FAST method selects the test parameters on each trial that maximizes information gain and provides significant increases in the efficiency of data collection (see Appendix for details).

Data analysis

Statistical analysis was performed using SPSS 20.0.0 (IBM Corp). Linear regressions were used to determine the effect of age on each speed separately. To aid comparison with previous studies, data were binned

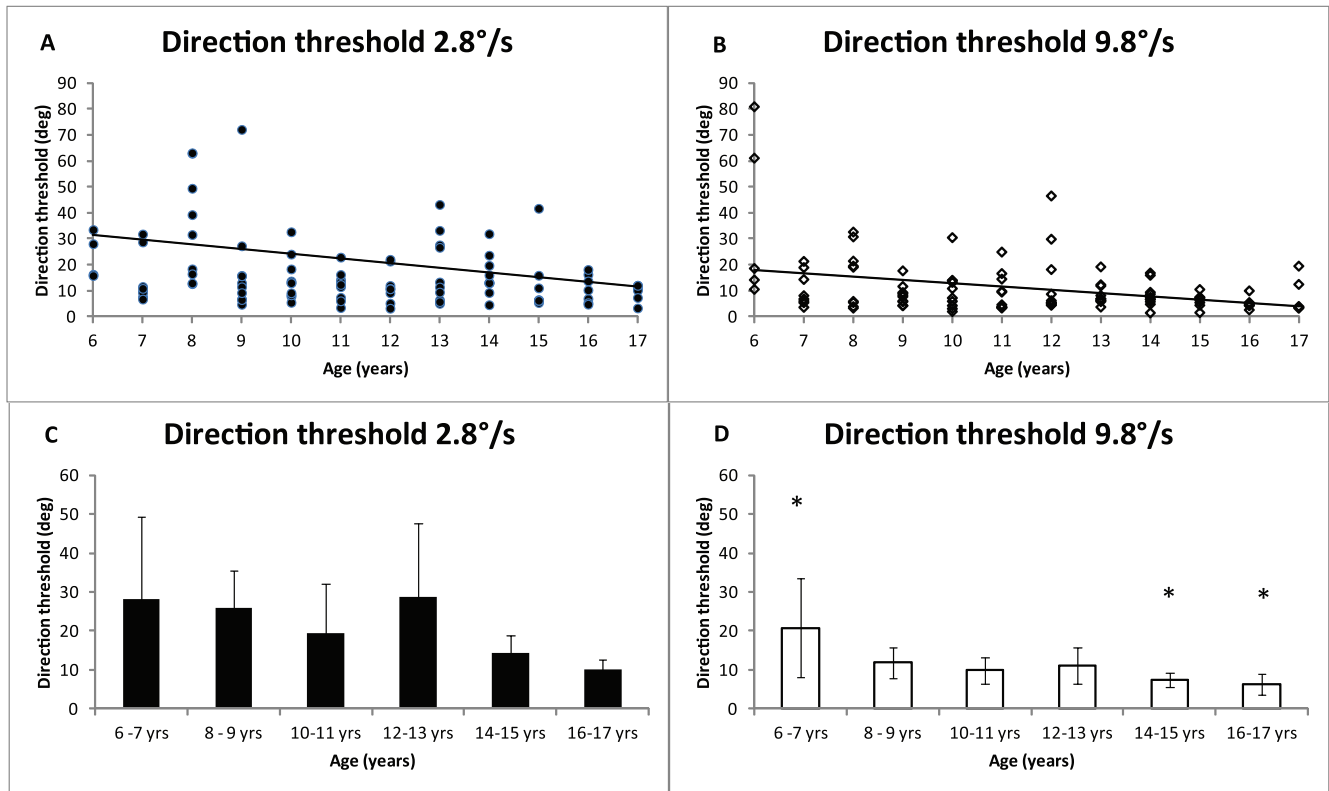


Figure 2. Direction discrimination thresholds as a function of age for $2.8^\circ/\text{s}$ and $9.8^\circ/\text{s}$. A and B show individual data, with regression lines. C and D show the mean data for observers binned according to age. Error bars show $\pm 95\%$ confidence intervals. Asterisks (*) indicate a statistically significant difference at $p < 0.005$ (ANOVA) between the two oldest age groups and the youngest age group. Significant post hoc Tukey comparisons show $p = 0.01$.

into six different groups of two years each; 6–7 years ($n = 13$), 8–9 years ($n = 19$), 10–11 years ($n = 20$), 12–13 years ($n = 20$), 14–15 years ($n = 18$), 16–17 years ($n = 13$). One-way ANOVA and post hoc Tukey tests were used to analyze differences between binned age groups. Paired t tests were used to test whether there was a difference between the two speeds.

Results

Direction discrimination threshold was estimated from the EN function at the point where external noise $= 0^\circ$. This point represents the minimum direction threshold for a noiseless stimulus. Figure 2A and 2B show direction discrimination thresholds as a function of age for individual observers for $2.8^\circ/\text{s}$ and $9.8^\circ/\text{s}$. The slopes on the fitted linear regression lines show a gradual improvement in direction discrimination with development for $2.8^\circ/\text{s}$ ($B_{2.8} = -1.6$, $t(102) = -1.8$, $p = 0.078$, $r^2 = 0.03$), and for $9.8^\circ/\text{s}$ ($B_{9.8} = -1.1$, $t(102) = -3.3$, $p = 0.001$, $r^2 = 0.1$), although there are large individual differences. Figure 2C and 2D show the mean direction discrimination threshold for binned age groups. At $9.8^\circ/\text{s}$, direction discrimination was signif-

icantly lower for the two oldest age groups compared with the youngest age group, ANOVA, $F(5, 97) = 2.9$, $p < 0.05$; post hoc Tukey, $p = 0.01$. In addition, Figure 2 also shows that direction discrimination thresholds were lower at the faster speed, paired t test: $t(102) = -3.5$, $p = 0.001$.

Sampling efficiency is a parameter (N_{samp}) estimated with EN analysis. Figure 3 shows sampling efficiency as a function of age for two different speeds. Figure 3A and 3B show individual sampling efficiencies, and it is clear that there is a significant increase in efficiency with age for both speeds (linear regression): $B_{2.8} = 0.2$, $t(102) = 2.3$, $p = 0.02$, $r^2 = 0.05$; $B_{9.8} = 0.4$, $t(102) = 3.4$, $p = 0.001$, $r^2 = 0.3$). Comparing different age groups, Figure 3D show that sampling efficiency is significantly higher for the 14–15 year olds than for the youngest age group, ANOVA, $F(5, 97) = 2.6$, $p < 0.05$; Post hoc Tukey $p = 0.05$. Furthermore, sampling efficiency was significantly lower at speed $2.8^\circ/\text{s}$ than at speed $9.8^\circ/\text{s}$ for all observers, paired t test: $t(102) = 4.1$, $p < 0.001$.

Internal noise (σ_{int}) is estimated with EN analysis. Figure 4 shows internal noise as a function of age for $2.8^\circ/\text{s}$ and $9.8^\circ/\text{s}$. Figure 4A and 4B show the individual data, and Figure 4C and 4D show binned data. As can be seen from Figure 4, there is no change in internal noise

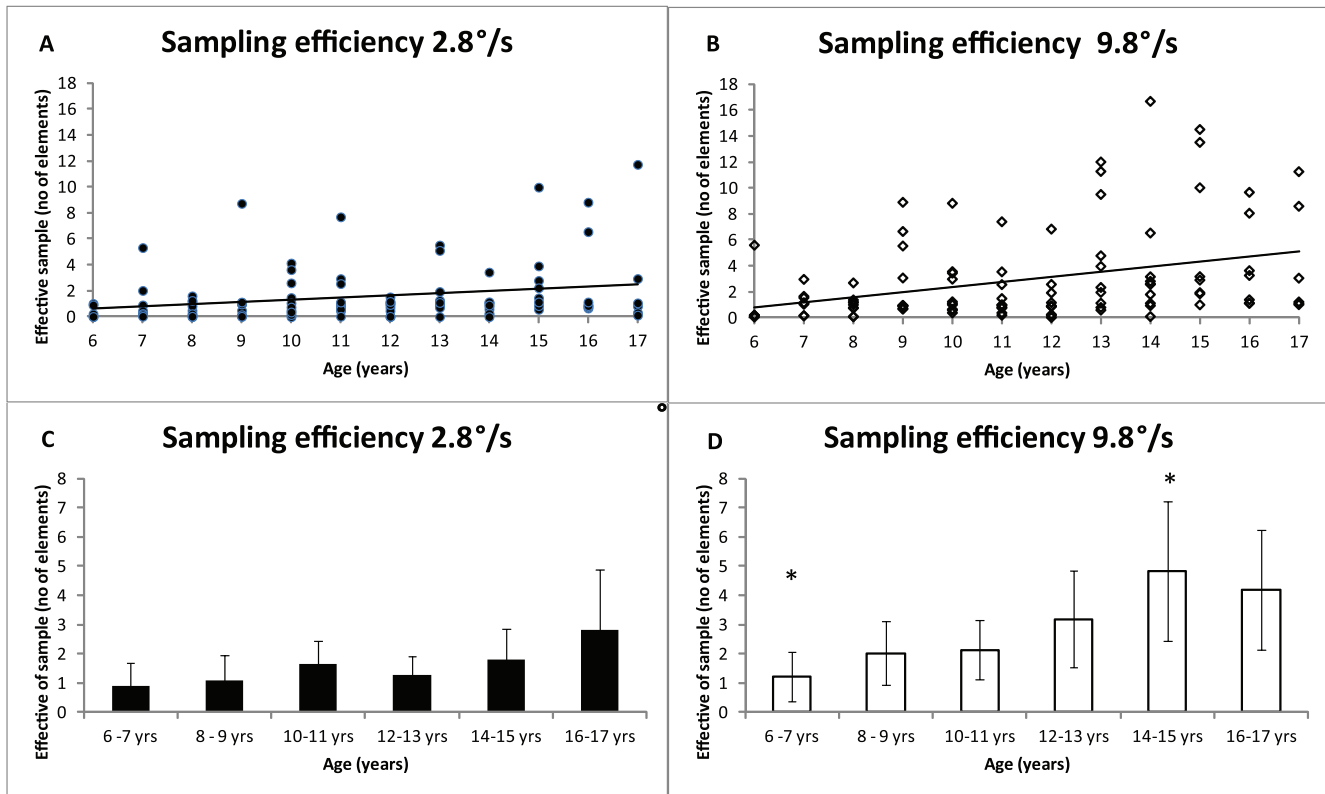


Figure 3. Sampling efficiency as a function of age at two different speeds. Figure A and B show the individual data for 2.8°/s and 9.8°/s speeds, respectively, with regression lines. Figure C and D show the mean data for participants binned according to age. Error bars show $\pm 95\%$ confidence intervals. Asterisks (*) indicate a statistically significant difference between age groups (ANOVA, $p < 0.05$).

with age, $B_{2.8} = -0.04$, $t(102) = -0.1$, $p = 0.9$, $r^2 = 0$; $B_{9.8} = -0.04$, $t(102) = -0.16$, $p = 0.9$, $r^2 = 0$, and there was no difference with speed, paired t test: $t(102) = -1.7$, $p = 0.09$.

Discussion

The current study investigated global motion perception of children aged 6–17 years at two different speeds (2.8°/s and 9.8°/s) using an EN model. The results show that the ability to discriminate the direction of global motion gradually matures in normal development, and that the youngest children need a larger angle to discriminate the direction of global motion. The EN analysis demonstrated that the improvement with age is due to improved sampling efficiency and not to reductions in internal noise.

Further, the performance is better at speed 9.8°/s than at 2.8°/s. The results extend our findings in aging, in which we showed that there is a decrease in direction discrimination in aging due to reduced sampling efficiency and also increased internal noise (Bogfjellmo et al., 2013). Our result is in agreement with Hadad, Maurer, and Lewis (2011) who found an immaturity in

sensitivity to the direction of global motion until the age of 12 years for speeds 4°/s and 18°/s. Our results are also in agreement with Banton et al. (2001), who performed a study on infants: They suggested that if the bandwidth of directionally selective motion mechanisms narrows with age, the direction discrimination sensitivity will increase. Broad bandwidths means that the precision of direction discrimination is poor as small differences in direction will elicit indistinguishable responses in a given detector (Banton et al., 2001), and therefore make the immature observer uncertain about the local direction of individual elements in the stimulus—i.e., internal noise. Kiorpes, Price, Hall-Haro, and Movshon (2012) also found that the ability to discriminate global direction develops gradually in macaque monkeys. They found that macaque monkeys reach maturity for complex motion direction discrimination at about 3 years of age due to the late maturation of extrastriate mechanisms. This age is approximately comparable to 13 human years (Boothe, Dobson, & Teller, 1985), in broad agreement with the present data. Hatta et al. (1998), who conducted physiological recordings from V1 neurons in infant Macaque monkeys ranging in age from 6 days to 8 weeks, showed that direction sensitivity was absent or very broad in one-week-old monkeys, but the band-

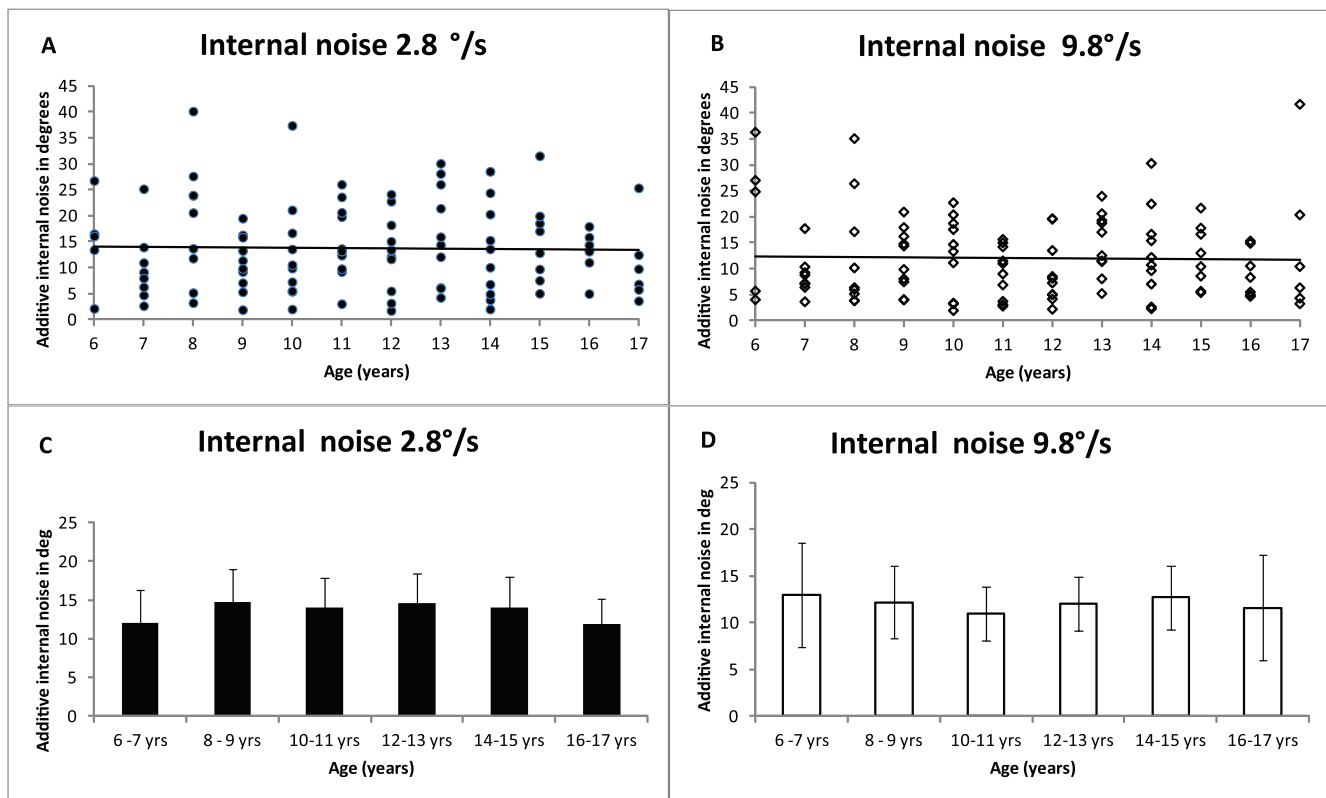


Figure 4. Internal noise as a function of age at two different speeds. Figure A and B show the individual data for 2.8°/s and 9.8°/s speeds, respectively, showing regression lines for the individual data. Figure C and D show the mean data for participants binned according to age. Error bars show $\pm 95\%$ confidence intervals.

width narrows with age and continues narrowing until maturation is reached.

Our data demonstrate that younger children need a larger angle to discriminate direction at speed 2.8°/s compared with speed 9.8°/s. The EN analysis determined that the reason for the improved global direction discrimination is a gradual development and improvement of sampling efficiency at both speeds, and that maturity is reached around the age of 14. Reduced sampling efficiency is equivalent to the observer using fewer elements in the stimulus to discriminate the global direction (Dakin et al., 2005). We have measured reduced sampling efficiency both in young children and in aging adults; this reduction could be related to an inconsistent decision-criterion dependent on the level of noise, or there is a mismatch between the decision template and the information contained in the stimulus (Bennett, Sekuler, & Ozin, 1999; Casco, Robol, Grassi, & Venturini, 2012; Legge, Kersten, & Burgess, 1987; Pardhan, Gilchrist, Elliott, & Beh, 1996; Simpson, Falkenberg, & Manahilov, 2003). Studies conducted on adults have found that reduced sampling efficiency may be due to neural dysfunction found in amblyopia (Giaschi, Regan, Kraft, & Hong, 1992) or optic neuritis (Parrish, 2005) amongst others. Although Hess, Wang, Demanins, Wilkinson, and Wilson (1999) found that

the reduction in suprathreshold form, when testing global shape detection in amblyopes, was due to increased internal noise rather than reduced sampling efficiency. This is in agreement with Knox, Ledgeway, and Simmers (2013), who suggested that internal noise in the earliest stages in motion perception is relatively high in amblyopes. In this study all observers went through a screening procedure to ensure that they were visually normal, and had normal visual health, which means that the improvement in sampling efficiency is due to normal development, rather than any observable pathology. The contrast of the present stimuli was relatively low (10% Michelson), and it is therefore possible that part of the improvement in direction discrimination could be related to an improvement in contrast sensitivity. We measured the contrast sensitivity function of each subject and found no significant change in either the area under the log contrast sensitivity function (Applegate, 1984) or in spatial frequency resolution, in agreement with previous studies, Ellemberg et al. (1999), suggesting that contrast sensitivity changes alone do not account for the improvement in motion sensitivity we observe.

Our results show that internal noise did not change with age or speed, and direction discrimination performance does not seem to depend on uncertainty

about each dot's local direction, which is in agreement with Falkenberg, Simpson, and Dutton (2013). Children between 6 and 17 are equally uncertain about local dot motion, suggesting that direction bandwidth is mature by the age of 6 years, consistent with primate data (Hatta et al., 1998). Although in principle, performance could be related to optical defocus due to immature accommodation or refractive status, all children in this study were screened and had best corrected Snellen visual acuity of 0.8 or better; therefore optical defocus is most likely not an issue. Reduced illumination and increased light scatter in the eye are also factors that can decrease performance; however, these ocular factors are unlikely in the young, visually healthy, observers we tested.

For all observers, direction discrimination sensitivity was lower (i.e., thresholds were higher) at $2.8^\circ/\text{s}$ compared to $9.8^\circ/\text{s}$. This is in agreement with previous studies on development of speed sensitivity (Ahmed et al., 2005; Manning et al., 2012) and work on adult observers (Bogfjellmo et al., 2013; McKee, Silverman, & Nakayama, 1986). Our study shows a gradual improvement for both speeds, although there are large individual differences in the population.

The children in this study needed a larger angle to discriminate direction at speed $2.8^\circ/\text{s}$ compared with speed $9.8^\circ/\text{s}$, which may be due to the lower sampling efficiency at speed $2.8^\circ/\text{s}$. The different stages of maturation of the visual functions may be due to the difference in selectivity of the various areas in the cerebral cortex that are devoted to the analysis of motion (Giaschi & Regan, 1997). The underlying speed mechanisms are computationally more complex than those coding direction. Neurons within MT may be less sharply tuned in children than adults, as there are fewer neurons tuned to slow speed compared with fast speeds in adult monkeys (Liu & Newsome, 2003). Less developed tuning may therefore have a greater impact on the discrimination of slower speeds, causing different rates of development of the pathways discriminating fast and slow speed (Ahmed et al., 2005; Manning et al., 2012). This also supports the idea of separate processing systems for fast and slow motion (Edwards, Badcock, & Smith, 1998; van der Smagt, Verstraten, Vaessen, van Londen, & van de Grind, 1999). Burr, Fiorentini, and Morrone (1998) hypothesized that the slow system is active at speeds below $3^\circ/\text{s}$ and as speed increases it involves the fast system to an upper limit of approximately $80^\circ/\text{s}$. Narasimhan and Giaschi (2012) tested densities of 1, 15, and 30 dots/ deg^2 at speeds $1^\circ/\text{s}$ and $4^\circ/\text{s}$ and found that for children at 5 and 6 years, both speed and density had significant effects on the thresholds, whereas adults seemed to be unaffected. Hadad et al. (2011) and Gunn et al. (2002) reported in their studies that the late maturation was due to the sparse patterns they used; 0.75 dots/ deg^2 and

4 dots/ deg^2 , respectively (Narasimhan & Giaschi, 2012). Our patterns were sparse; they had a density of 3.8 dots/ deg^2 for both speeds; however, Dakin et al. (2005) showed that the number of dots present in the EN stimuli limits both local noise and global sampling regardless of their density or size of field they occupy.

Since a gradual improvement was observed for both speeds, it is unlikely that performance is limited by non-visual factors such as response bias, attention, memory, motivation, or subjects' understanding of the test. All observers in this study had a short practice run before they started to make sure they understood the test. Abramov et al. (1984) found in his study that good psychophysical data on children could be collected within a reasonably short time. The test time in our study was approximately 3 min for each trial run, and we therefore suppose that the developmental improvements we see in this study are visual in nature and not cognitive. The most parsimonious explanation of the speed difference is that the lifetime of each dot was fixed at three video frames; thus, slower moving dots traveled a shorter overall distance than faster moving dots. It is therefore possible that longer trajectories contain more spatial information than do shorter trajectories.

Conclusion

Global motion perception improves gradually during development and matures by the age of 14 years. The improvement in global motion perception is underpinned by a steady increase in the efficiency with which direction signals are pooled, whereas internal noise does not change after the age of 6. This suggests that global motion pooling processes mature later than local motion processing, a finding in line with previous studies (Armstrong et al., 2009; Ellemberg et al., 1999; Gunn et al., 2002; Manning et al., 2012; Parrish, 2005).

Keywords: motion perception, development, sampling efficiency, internal noise, random dot kinematogram

Acknowledgments

This research was supported by NIH R01 EY018664 to Peter J. Bex. We thank Tor Martin Kvikstad for helpful suggestions.

Commercial relationships: none.

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Appendix

Equivalent noise (EN) implementation in FAST

A variety of well-known adaptive procedures have been developed to increase the efficiency with which a psychometric function can be estimated during an experiment; for review see (Treutwein, 1995; Leek, 2001). More recently, several authors have proposed efficient methods to estimate behavioral functions. Behavioral functions such as the TvC function (Lesmes, Jeon, Lu, & Doshier, 2006), the Contrast Sensitivity Function (Lesmes, Lu, Baek, & Albright, 2010), ellipsoidal threshold functions (Kujala & Lukka, 2006), and a general FAST toolbox for rapid assessment of behavioral functions has been implemented in MatLab (Vul, Bergsma, & MacLeod, 2010).

These approaches specify a behavioral function that describes threshold (e.g., contrast detection threshold) as a function of an experimental variable (e.g., spatial frequency). Instead of measuring a threshold at each of a set of predetermined levels (e.g., six spatial frequencies log-spaced between 0.5 and 16 c/°), these approaches exploit information about the whole function from each data point. For each trial, the potential information gained from multiple alternative possible stimuli (e.g., spatial frequency and contrast combinations) is estimated. The stimulus that maximizes the certainty about the function parameter values is then selected for the next trial, and this process is repeated until the end of the experiment. This process allows an experiment to converge on an estimate of the function in many fewer trials than does a conventional experiment.

We implemented the EN algorithm with the FAST toolbox (Vul et al., 2010). The EN function described direction discrimination threshold as a function of external noise:

$$\sigma_{\theta} = \sqrt{\frac{\sigma_{\text{int}}^2 + \sigma_{\text{ext}}^2}{N_{\text{samp}}}} \quad (\text{A1})$$

where σ_{θ} is the direction discrimination threshold; σ_{int} is internal noise, the directional uncertainty in the observer's visual system; σ_{ext} is external noise, the variance of the direction distribution from which dot directions were drawn; and N_{samp} is the number of dots used by the observer to estimate the global direction of all dots.

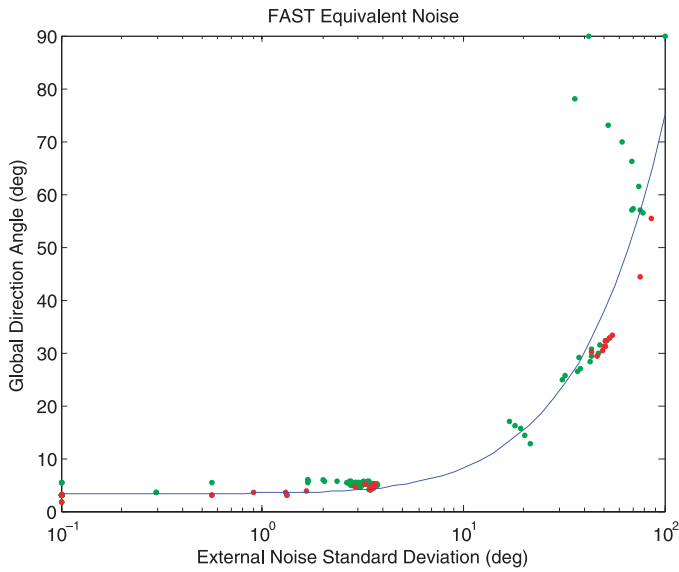


Figure A1. EN Analysis measured with FAST in a simulated experiment with 100 trials. Each data point indicates the direction angle and external noise level on one trial: Green data points indicate trials on which the response was correct; red points represent incorrect trials. The curve shows the best fitting EN function. See text for details.

The probability of a correct response on any trial is:

$$p = 0.5 + 0.5 * \exp\left(-\frac{(\sigma_\theta - \theta)^2}{\sigma_s^2}\right) \quad (A2)$$

where θ is the global direction angle of the stimulus, and σ_s is the slope of the psychometric function. The purpose of the experiment is to estimate σ_{int} , N_{samp} , and σ_s , which are unknown, by varying θ and σ_{ext} and observing p . The FAST algorithm selects θ and σ_{ext} each trial.

Figure A1 shows the results of a simulated experiment in which the internal noise, sampling efficiency parameters, and the slope of the psychometric function were respectively fixed at 5° , 2° —based on previous data (Mareschal, Bex, & Dakin, 2008), and 3.5° —based on QUEST (Watson & Pelli, 1983). Each data point indicates the angle and external noise level on one trial: Green data points indicate trials on which the response was correct, and red points represent incorrect trials. The curve shows the best fitting EN function after 100 trials.

Figure A2 shows the distribution of the absolute error between the FAST estimate and the true value of each parameter as a function of the number of trials completed. Error rapidly decreases as the number of trials increases and the algorithm converges to less than 10% of the true parameter values within around 40 trials. For internal noise and sampling efficiency, median error is less than 20% of the true value after 24 trials and stabilizes at around 10% of the true value

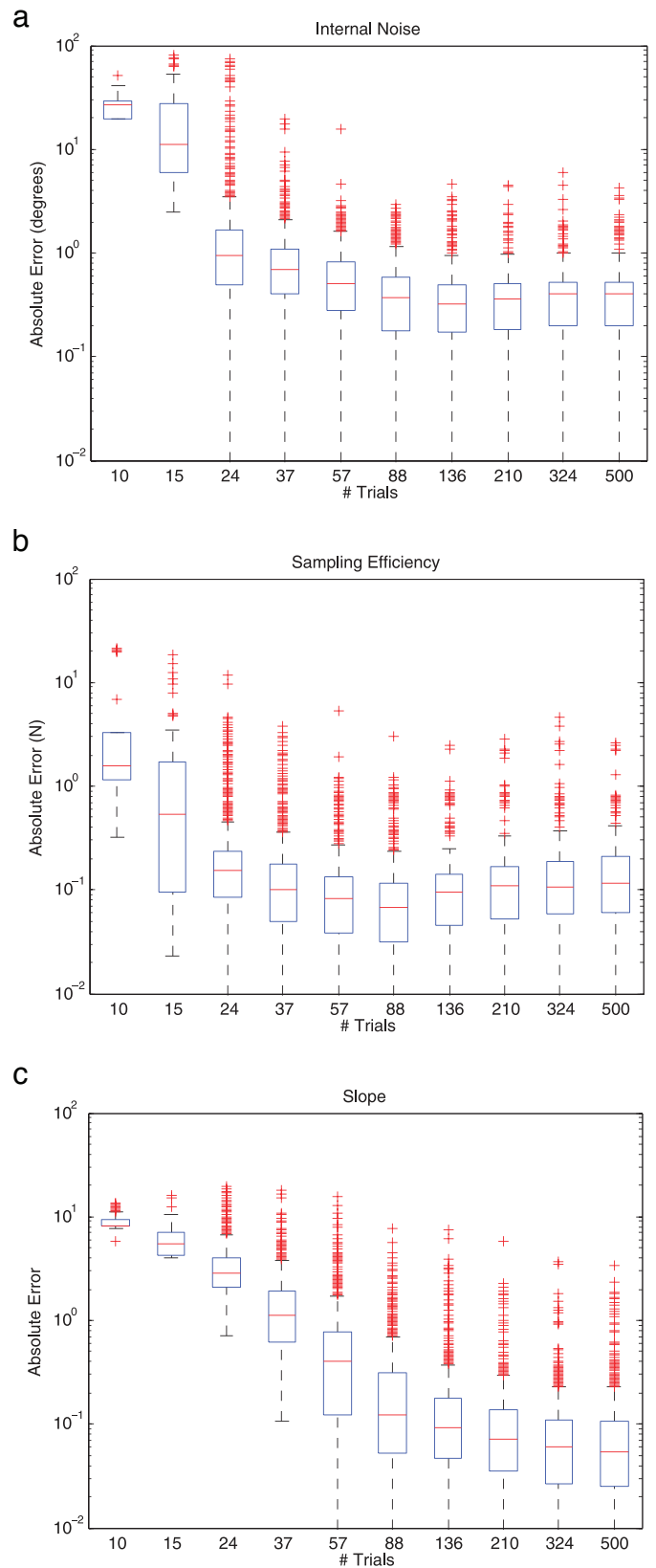


Figure A2. Box plots of the error between the FAST estimate and the true value of (a) Internal Noise, (b) Sampling Efficiency, and (c) Psychometric Function Slope as a function of the number of trials in an experiment. The central red line is the median, the

←
 edges of the box are the 25th and 75th percentiles, the black whiskers extend to the most extreme data points not considered outliers, and red plus symbols indicate outliers, determined automatically by MatLab.

after around 40 trials. Error on slope also converges to within 10% of the true value within 40 trials, but continues to converge with additional trials. We therefore used a conservative 50 trials in the experiment.

Figure A3 shows typical data from a 35-year-old observer from (Bogfjellmo et al., 2013), plotted as in Figure A1.

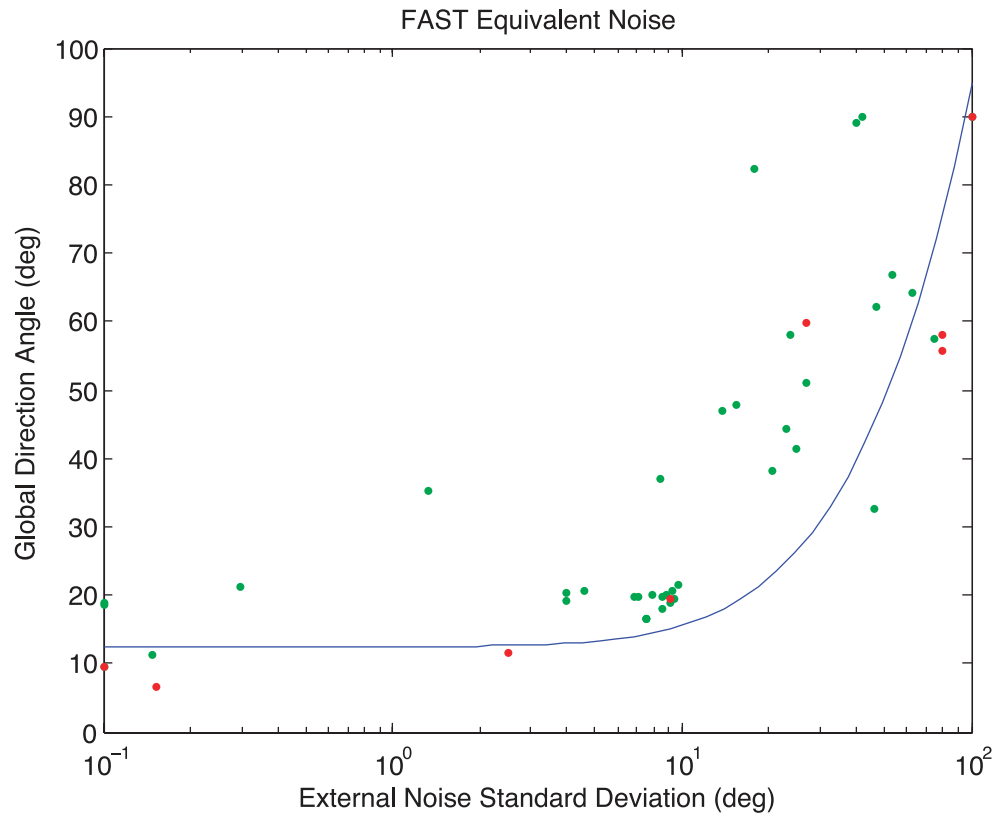


Figure A3. As Figure A1 except the data are for a 35-year-old naive observer.