# Development of sampling efficiency and internal noise in motion detection and discrimination in school-aged children

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A B S T R A C T

The aim of this study was to use an equivalent noise paradigm to investigate the development and maturation of motion perception, and how the underlying limitations of sampling efficiency and internal noise effect motion detection and direction discrimination in school-aged children (5–14 years) and adults. Contrast energy thresholds of a 2 c/deg sinusoidal grating drifting at 1.0 or 6.0 Hz were measured as a function of added dynamic noise in three tasks: detection of a drifting grating; detection of the sum of two oppositely drifting gratings and direction discrimination of oppositely drifting gratings. Compared to the ideal observer, in both children and adults, the performance for all tasks was limited by reduced sampling efficiency and internal noise. However, the thresholds for discrimination of motion direction and detection of moving gratings show very different developmental profiles. Motion direction discrimination continues to improve after the age of 14 years due to an increase in sampling efficiency that differs with speed. Motion detection and summation were already mature at the age of 5 years, and internal noise was the same for all tasks. These findings were confirmed in a 1-year follow-up study on a group of children from the initial study. The results support suggestions that the detection of a moving pattern and discriminating motion direction are processed by different systems that may develop at different rates.

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## 1. Introduction

The ability to perceive motion is a vital and fundamental visual function in humans and several areas in the cerebral cortex are devoted to the analysis of motion. Clinical investigations of vision in children have a tendency to concentrate on visual acuity measurements, and although important, acuity tells us little or nothing about how children perceive the moving world they constantly experience. Although rare, the inability to perceive motion can be severely disabling in everyday life (Zihl, von Cramon, & Mai, 1983). More subtle motion deficits have been in development conditions like amblyopia (Giaschi et al., 1992; Knox, Ledgeway, & Simmers, 2013; Simmers et al., 2003), strabismus (Norcia, 1996), dyslexia (Benassi et al., 2010; Demb et al., 1998; Edwards et al., 2004), autism (Annaz et al., 2010; Koh, Milne, & Dobkins, 2010; Pellicano et al., 2005; Spencer et al., 2000) and cerebral dysfunction (Ahmed & Dutton, 1996; Dutton et al., 2004; Guzzetta et al., 2009; Weinstein et al., 2012). In adults motion perception is impaired in

normal ageing (Bogfjellmo, Bex, & Falkenberg, 2013; Hutchinson et al., 2012), glaucoma (Bullimore, Wood, & Swenson, 1993; Falkenberg & Bex, 2007), multiple sclerosis (Regan, Kothe, & Sharpe, 1991) and Alzheimer's disease (Mapstone, Dickerson, & Duffy, 2008). These disruptions of motion perception suggest that motion perception may be vulnerable in typical visual development, and that reduced sensitivity to motion could be used as an indicator of neurodevelopmental or pathological disorders. To enable the separation of typical and atypical development, it is necessary to understand how normal motion perception develops and matures in childhood.

In typical development, detection of moving patterns and discrimination of motion direction continues to improve during childhood (Armstrong, Maurer, & Lewis, 2009; Bogfjellmo, Bex, & Falkenberg, 2014; Boot et al., 2012; Ellemberg et al., 1999, 2003, 2004; Giaschi & Regan, 1997; Gordon & McCulloch, 1999; Hadad, Maurer, & Lewis, 2011; Hayward et al., 2011; Manning, Aagten-Murphy, & Pellicano, 2012; Meier & Giaschi, 2014; Narasimhan & Giaschi, 2012; Parrish et al., 2005; Schrauf, Wist, & Ehrenstein, 1999). Different aspects of motion perception develop and reach adult levels at different times, ranging from 3 years (Parrish et al., 2005) to 15 years (Schrauf, Wist, & Ehrenstein, 1999),

depending on the specific psychophysical task and stimulus parameters. Generally, detection of moving patterns develops and matures to adult levels earlier than direction discrimination. Young children show elevated thresholds for detecting global motion coherence (Boot et al., 2012; Ellemberg et al., 2003, 2004; Falkenberg, Dutton, & Simpson, 2010; Gunn et al., 2002; Hadad, Maurer, & Lewis, 2011; Meier & Giaschi, 2014; Narasimhan & Giaschi, 2012), speed discrimination (Ahmed et al., 2005; Hayward et al., 2011; Manning, Aagten-Murphy, & Pellicano, 2012; Narasimhan & Giaschi, 2012; Parrish et al., 2005) and direction discrimination (Armstrong, Maurer, & Lewis, 2009; Ellemberg et al., 2003; Giaschi & Regan, 1997). Ellemberg et al. (1999) found that critical flicker fusion frequency and contrast thresholds for detecting gratings that flickered at high temporal frequencies (20.0 and 30.0 Hz) were mature at 4 years, whereas for 5.0 and 10.0 Hz adult levels were not achieved until 7 years of age. That temporal sensitivity is immature in 5-year-olds was later confirmed by the same group (Ellemberg et al., 2003, 2004). Some studies show that motion coherence thresholds are less mature at slow speeds (Gunn et al., 2002; Hayward et al., 2011; Manning, Aagten-Murphy, & Pellicano, 2012; Meier & Giaschi, 2014; Narasimhan & Giaschi, 2012; Parrish et al., 2005), but have been found to reach adult values by 7–8 years (Giaschi & Regan, 1997; Hayward et al., 2011; Parrish et al., 2005) when speed thresholds are measured. Recently, a rather novel technique of measuring reaction time to fixation showed that the motion processing matured at eight years old (Boot et al., 2012).

While it is evident that motion sensitivity is immature in childhood, the underlying mechanisms and limiting factors in normal development still require elucidation. One approach to studying such limiting factors is through comparing real observer performance to that of an ideal observer. The ideal observer is derived through mathematical statistics (Whalen, 1971) and is completely non-arbitrary. Humans differ in two ways from the ideal observer who uses all the information available (Bennett, Sekuler, & Ozin, 1999; Burgess et al., 1981; Green & Swets, 1966; Legge, Kersten, & Burgess, 1987; Pelli, 1990; Pelli & Farell, 1999). First, real observers behave as though the stimulus contains more noise than it really contains. Their performance can be modeled by assuming that internal noise has been added to the stimulus. Sources of internal noise include random optical, photon and neuronal noise (Barlow, 1978; Pelli, 1990). Second, real observers are inefficient samplers who fail to use all the information delivered in the stimulus. Reduced sampling efficiency can be due to neural factors (cortical immaturities, multiplicative neural noise) in the visual system or cognitive factors such as variable attention or inefficient cross-correlation between the delivered noisy signal and the known signal template (Bennett, Sekuler, & Ozin, 1999; Burgess & Colborne, 1988; Legge, Kersten, & Burgess, 1987). If a fixed signal ("signal known exactly") is used in an experiment, the ideal strategy is to cross-correlate the stimulus with a template of the signal. An ideal observer will use the true signal as the template, but a real observer will not remember the signal perfectly and hence the template will not be identical to the signal. This is a major cause of sampling inefficiency. Many studies have investigated the limiting factors of human pattern detection and discrimination using the equivalent noise (EN) model (Bennett, Sekuler, & Ozin, 1999; Dakin, Mareschal, & Bex, 2005; Falkenberg & Bex, 2007; Pardhan, 2004; Simpson, Falkenberg, & Manahilov, 2003). The detection and discrimination of moving grating patterns was specifically studied by our group (Simpson, Falkenberg, & Manahilov, 2003) the EN model. The EN model has also recently been applied developmentally to study global motion perception (Bogfjellmo, Bex, & Falkenberg, 2014), where direction discrimination improves in childhood due to improved sampling efficiency. Further, it has been found that both internal noise and sampling efficiency limits

detection and discrimination in older adults (Bennett, Sekuler, & Ozin, 1999; Bogfjellmo, Bex, & Falkenberg, 2013; Falkenberg & Bex, 2007; Pardhan, 2004; Pardhan et al., 1996). In the context of this approach, we can ask whether the immaturity observed in previous developmental studies of motion perception is due to increased levels of internal noise, or to poor sampling efficiency, or both.

The present study applies an EN model to investigate the limiting mechanisms underlying the development of motion detection and discrimination in typically developing school-aged children. A 1-year follow-up study was performed on a group of children to investigate longitudinal changes in motion detection and discrimination. Besides the utility of these data for determining the mechanisms underlying the normal development of motion perception, these data will also be used as a reference for children with developmental disorders (paper in preparation).

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Subjects

168 children (85 girls) aged 5–14 years took part in the study. The children were divided into 10 groups according to age, 5 years ($n = 15$); 6 years ($n = 11$); 7 years ($n = 17$); 8 years ($n = 20$); 9 years ($n = 22$); 10 years ($n = 20$); 11 years ($n = 19$); 12 years ($n = 17$); 13 years ($n = 14$) and 14 years ($n = 13$). Child observers were recruited from the out-patients department at the Royal Hospital for Sick Children in Glasgow, from children of staff at Glasgow Caledonian University and from visitors at the Glasgow Science Centre. Informed assent was sought from all child observers and parents/guardians gave consent. 15 naive adult observers (age $29.3 \pm 4.6$ years) from Glasgow Caledonian University also participated with informed consent. Approval to approach children and parents was granted from all of the above institutions and the tenets of the Declaration of Helsinki were followed. Observers wore their current spectacle correction if required. All observers were screened for visual abnormalities by an optometrist (HKF). To be included in the study, observers had to meet the following criteria: VA better than 1.0 Snellen equivalent (0.8 for the 5 year olds) and monocular VA difference <0.1 logMAR using Glasgow Acuity Cards (GAC score = 1 – log MAR); no strabismus or heterophorias <$10\Delta D$ (Cover Test); normal history of ophthalmic pathology and birth.

#### 2.1.2. Stimuli

Upward, downward or flickering gratings were generated by a computer with an 8 bit video board and presented on a high resolution monitor (19″, Ilyama Vision Master Pro 450, 640 × 480 pixels) with a refresh rate of 120 Hz. The VGA RGB outputs were combined electronically (Pelli & Zhang, 1991), which gave 12 bits of luminance control, and an optimum palette of 256 luminances (out of 4096) was used. The mean luminance was 30 cd/m², and the display was calibrated with a luminance meter (LS-100; Konica Minolta, Osaka, Japan). The stimulus was viewed binocularly from a head and chin rest 105 cm away in a dimly lit room where the uniform gray background behind the monitor matched the luminance of the display. A central fixation mark was present for the duration of each trial.

The stimulus was a moving or flickering grating with added dynamic noise (Fig. 1), presented within a 5 deg circular window for a total of 333 ms (20 movie frames). The signal grating was a 2 c/deg Gabor patch drifting at 1.0 Hz or 6.0 Hz. The added dynamic Gaussian white noise was generated by a multiply-with-carry generator (Marsaglia, 1994) in combination with the