Vision Research 127 (2016) 18–27

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Global motion perception in children with amblyopia as a function of spatial and temporal stimulus parameters

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ARTICLE INFO

Article history:
Received 1 April 2016
Received in revised form 27 May 2016
Accepted 28 June 2016
Available online 25 July 2016

Keywords:
Amblyopia
Global motion perception
Psychophysics
Visual development

ABSTRACT

Global motion sensitivity in typically developing children depends on the spatial (Δx) and temporal (Δt) displacement parameters of the motion stimulus. Specifically, sensitivity for small Δx values matures at a later age, suggesting it may be the most vulnerable to damage by amblyopia. To explore this possibility, we compared motion coherence thresholds of children with amblyopia (7–14 years old) to age-matched controls. Three Δx values were used with two Δt values, yielding six conditions covering a range of speeds (0.3–30 deg/s). We predicted children with amblyopia would show normal coherence thresholds for the same parameters on which 5-year-olds previously demonstrated mature performance, and elevated coherence thresholds for parameters on which 5-year-olds demonstrated immaturities. Consistent with this, we found that children with amblyopia showed deficits with amblyopic eye viewing compared to controls for small and medium Δx values, regardless of Δt value. The fellow eye showed similar results at the smaller Δt. These results confirm that global motion perception in children with amblyopia is particularly deficient at the finer spatial scales that typically mature later in development. An additional implication is that carefully designed stimuli that are adequately sensitive must be used to assess global motion function in developmental disorders. Stimulus parameters for which performance matures early in life may not reveal global motion perception deficits.

1. Introduction

Amblyopia is a visual developmental disorder characterized by poor visual acuity in one eye that cannot be corrected immediately with glasses, with a typical onset between the ages of six months and eight years (von Noorden, 1990). In addition to this diagnostic acuity deficit, children and adults with amblyopia show deficits in spatial vision, including contrast sensitivity (Hess & Howell, 1977; Levi & Harwerth, 1977), Vernier acuity (Birch & Swanson, 2000; Levi & Klein, 1985), form integration (Mansouri & Hess, 2006), orientation processing (Husk & Hess, 2013), contour integration (Chandna, Pennefather, Kovacs, & Norcia, 2001) and static angle discrimination (Levi & Tripathy, 2006). Amblyopia is also associated with deficits in motion perception, including motion aftereffects (Hess, Demanins, & Bex, 1997), oscillatory movement displacement (Buckingham, Watkins, Bansal, & Bamford, 1991; Kelly & Buckingham, 1998), motion-defined form (Giaschi, Regan, Kraft, & Hong, 1992; Hayward, Truong, Partanen, & Giaschi, 2011; Ho et al., 2005; Wang, Ho, & Giaschi, 2007), maximum motion displacement (Ho & Giaschi, 2006, 2007; Ho et al., 2005) and attentive motion tracking (Ho et al., 2006). Global motion perception has been reported to be deficient in many studies (Aaen-Stockdale & Hess, 2008; Constantinescu, Schmidt, Watson, & Hess, 2005; Hou, Pettet, & Norcia, 2008; Simmers, Ledgeway, & Hess, 2005; Simmers, Ledgeway, Hess, & McGraw, 2003; Simmers, Ledgeway, Mansouri, Hutchinson, & Hess, 2006; Thompson et al., 2011), but relatively spared in others (Ho et al., 2005, 2006). Here we explore this inconsistency by considering the effects of stimulus parameters with different developmental trajectories, as well as clinical factors, on global motion direction discrimination thresholds in children with amblyopia.

In the typical development of motion perception, speed-tuned maturation is observed such that children tend to reach adult-like performance for slow-speed stimuli later in life than stimuli presented at faster speeds. This has been demonstrated in a wide range of tasks including global motion (Bogfjellmo, Bex, & Falkenberg, 2014; Ellemberg et al., 2004; Narasimhan & Giaschi, 2012), motion-defined form (Hayward et al., 2011), radial flow

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http://dx.doi.org/10.1016/j.visres.2016.06.011
0042-6989/

(Joshi & Falkenberg, 2015), and speed discrimination (Ahmed, Lewis, Ellemberg, & Maurer, 2005; Manning, Aagten-Murphy, & Pellicano, 2012). Hou, Gilmore, Pettet, and Norcia (2009) found visually evoked potential (VEP) responses in 4–6 month old infants were maximal to large spatial displacements, suggesting sensitivity for faster speeds matures sooner than sensitivity to slower speeds. The last-in-first-out principle of the Detroit model of development (Levi & Carkeet, 1993) proposes that for disorders that emerge after birth, such as amblyopia, aspects of visual function that mature later in development are the most vulnerable to disruption. Consistent with this model, children with developmental disorders have shown speed-tuned deficits for slow, but not fast, motion tasks (e.g., amblyopia: Hayward et al., 2011; autism: Manning, Charman, & Pellicano, 2013; reading difficulties: Edwards et al., 2004; Kassaliete, Lacis, Fomins, & Krumina, 2015).

On a global motion task, however, motion coherence thresholds are not purely speed-dependent. The speed of a motion stimulus depends on a ratio of spatial and temporal displacements, that is, the distance a dot is offset between each pair of animation frames (Δx), and the duration of a single animation frame before the next is displayed (Δt). In adults, coherence thresholds vary as a function of Δx and Δt displacement components comprising a speed (Arena, Hutchinson, & Shimozaki, 2012). Young macaques (Kiorpes & Movshon, 2004) and children (Meier & Giaschi, 2014) also show this effect. Moreover, depending on the spatio-temporal parameters tested, children may or may not show adult-like coherence thresholds. For example, 5-year-old children's performance is mature for larger Δx displacements regardless of Δt (Meier & Giaschi, 2014), which means for a given speed, whether a child displays mature performance or not can depend on the Δx parameter of the motion stimulus. This suggests that critical periods in development rely on the spatial and temporal frequency content of a motion sequence and not solely on motion speed. In turn, this can clarify discrepancies in prior work that is not consistent with the idea that slow speeds take longer to mature. For example, Hadad, Maurer, and Lewis (2011) found no difference in maturational rates for fast and slow speeds, using relatively small Δx displacements to create both speeds, while Parrish, Giaschi, Boden, and Dougherty (2005) found young children showed mature performance using a slow speed stimulus with a larger Δx. This demonstrates that in addition to motion speed, the spatial displacements used to create a speed must also be taken into account when studying development.

Likewise, differences in Δx may explain why some studies have not shown global motion deficits in children with amblyopia. Studies using the Δx values used by Parrish et al. (2005) found no significant group difference in coherence thresholds between children with amblyopia and age-matched controls (Ho et al., 2005, 2006; Wang et al., 2007). Given that young children demonstrate mature performance for this global motion stimulus, a lack of deficit in children with amblyopia is not surprising by the last-in-first-out principle. On the other hand, studies that have found elevated thresholds in both the clinically affected and fellow eyes of participants with amblyopia (e.g., Constantinescu et al., 2005; Simmers et al., 2003, 2006) have employed global motion stimuli with faster speeds. If the aspects of motion perception that typically mature early are robust to the effects of amblyopia, these apparently discrepant findings may be resolved: deficits in global motion perception may not be detected, regardless of speed, with a stimulus that is not sensitive to developmental differences.

The purpose of this study was to determine the spatio-temporal parameters at which children with amblyopia demonstrate global motion perception deficits. We selected a subset of the Δx and Δt combinations tested previously in typically-developing 5-year olds (Meier & Giaschi, 2014), and measured motion coherence thresholds for children with amblyopia and age-matched controls. Consistent with the last-in-first-out principle, we hypothesized that children with amblyopia would show selective deficits for parameter combinations that were found to be immature in typically-developing 5-year-olds in our prior study.

In addition to group differences, we sought to determine whether motion perception deficits in children with amblyopia were predicted by clinical factors such as etiological subtype, binocular function and depth of amblyopia. Performance thresholds in aspects of spatial vision like Vernier acuity have been shown to vary by subtype, often such that participants with strabismic amblyopia tend to perform worse than participants with anisometropic amblyopia (e.g., Levi & Klein, 1982), regardless of age of onset (Birch & Swanson, 2000). There is some evidence that children with anisometropic amblyopia perform poorer on global motion tasks than children with strabismic amblyopia (Ho et al., 2005, 2006), while a study with macaques suggests greater deficits in strabismic amblyopia, particularly in the fellow eye at small values of Δx (Kiorpes, Tang, & Movshon, 2006). Other studies have found no differences between subtypes on motion tasks (e.g., Giaschi, Chapman, Meier, Narasimhan, & Regan, 2015; Simmers et al., 2003, 2005) and motion deficits have been shown in anisometropic, strabismic, and ansio-strabismic amblyopia (e.g., Aaen-Stockdale & Hess, 2008; Simmers et al., 2006; Thompson et al., 2011), as well as deprivation amblyopia (Constantinescu et al., 2005; Ellemberg, Lewis, Maurer, Brar, & Brent, 2002). There is some suggestion that binocularity, rather than etiology, may be a better predictor of deficits in the amblyopic visual system (McKee, Levi, & Movshon, 2003). Lack of binocularity or stereoacuity in participants with amblyopia has been shown to correlate with motion perception deficits (e.g., Knox, Ledgeway, & Simmers, 2013), but it has also been shown to correlate with *better* global motion perception (e.g., Ho et al., 2005), while other studies show no correlation (e.g., Ho et al., 2006). Finally, motion perception deficits may be indicative of deeper or more treatment-resistant amblyopia (Giaschi et al., 1992, 2015; Ho et al., 2005), so we assessed whether a relationship exists between motion deficits and amblyopic eye visual acuity, interocular visual acuity difference, and the number of months a child had undergone occlusion therapy.

2. Methods

2.1. Participants

Informed consent was first obtained from the parents or guardians of all children who participated in this research, followed by assent from the participants. This work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.1. Patient group

Children with a history of unilateral amblyopia and no developmental, cognitive, or additional visual disorders aside from strabismus were recruited from the Ophthalmology Clinic at BC Children's Hospital. Twenty-seven children participated in the study; data from one child with a developmental disorder and one child with deprivation amblyopia were discarded, and two children had attention-related difficulties with conducting the full procedure, leaving a total of 23 children with data available for analysis (*M* age = 10.7 years, *SD* = 2.3, *range* = 7.1–14.7).

Patient characteristics are listed in Table 1. The initial diagnosis of amblyopia was made by an ophthalmologist based on a best-corrected Snellen acuity of 20/30 or worse in the amblyopic eye, 20/25 or better in the fellow eye and a minimum two-line difference in Snellen acuity (equivalent to 0.2 logMAR) between the