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Reach-to-precision grasp deficits in amblyopia: Effects of object contrast and low visibility

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A R T I C L E I N F O

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A B S T R A C T

Adults with a history of unilateral amblyopia and abnormal binocularity have a range of visual deficits, with some of the 'higher' levels ones generalizing to their dominant (non-amblyopic) eye and linked to widespread binocular cortical network dysfunctions. Our interests are in how these problems also impact on their hand action control in real-world situations. We investigated whether eye-hand coordination deficits, known to exist in amblyopia when goal objects are presented under full-lighting and at high contrast, are exacerbated under low object-background contrast or in dim lighting/low visibility conditions. Hand movement parameters were recorded and quantified in 13 amblyopia and 13 control subjects while they reached-to-precision grasp objects using both eyes together or just their dominant or amblyopic/non-dominant eye alone under these 3 task conditions. Compared to controls, the amblyopia subjects spent significantly longer in preparing their movements, in the initial (planned) periods of their reach and grasp and in applying their grip, while making more reach and grasp errors under all 3 views and tasks. Deficits in planning and controlling the grasp were also *selectively* accentuated in the low contrast condition, but with no evidence of relatively worse performance under low environmental illumination. We suggest that the dysfunctions in amblyopia are associated with generalized difficulties in obtaining reliable visual evidence about the target's 3D properties during movement planning and in selecting and guiding the proper course of action, especially when segregating the object from background is more challenging.

1. Introduction

Amblyopia is a common neurodevelopmental disorder characterized by reduced vision, usually in one eye, that cannot be immediately improved by optical correction. It results from abnormal binocular visual experience associated with the presence of image misalignment (due to strabismus), blur (from unequal refractive error/anisometropia) or deprivation (e.g., due to cataract), alone or in combination, in infancy or early childhood. Evidence suggests that the reduced vision that people with amblyopia encounter in their affected eye occurs along two major, independent dimensions (McKee, Levi, & Movshon, 2003); loss of spatial (e.g., letter) acuity and of contrast sensitivity, this latter being most evident at higher spatial scales, but often occurring at low spatial frequencies as well in all amblyopia sub-types (Hess & Howell, 1977; Levi & Harwerth, 1977, 1980). The visual acuity loss is used as the widely accepted clinical definition of the presence and severity of the disorder. Although there is evidence that losses occurring along a third major dimension, namely the presence or absence of binocularity (e.g., stereo acuity), is a better indicator of the overall visual status of both strabismic and non-strabismic amblyopia populations (McKee, Levi, & Movshon, 2003).

On the other hand, it is now also established that reduced amblyopic eye vision extends to certain grouping tasks based on the integration or segregation of signal from noise over quite wide regions of space, and which cannot be explained by the more 'basic' (i.e., first-order) losses in visual acuity and contrast detection present (for recent review, see Hamm et al., 2014). Some of these visual impairments in unilateral amblyopia – for example, in positional uncertainty/crowding (Levi & Klein, 1985) and in 'global' orientation, contour/shape and motion perception (e.g., Giaschi et al., 1992; Kovács et al., 2000; Mansouri, Allen, & Hess, 2005; Simmers, Ledgeway, & Hess, 2005; Simmers et al., 2003; Wong, Levi, & McGraw, 2001) – and in others with significant attentional-system demands (Farzin & Norcia, 2011; Ho et al., 2006; Sharma, Levi, & Klein, 2000; Thiel & Sireteanu, 2009) have been shown to occur, if to a lesser extent, in the 'normal' (dominant or fellow/fixing) eye as well. This suggests that neurodevelopmental defects in amblyopia are not confined to 'lower' visual

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processing areas of calcarine (V1/V2) cortex, but extend to – and may be exacerbated in – the functional relations between extrastriate occipito-temporal (ventral) and occipito-parietal (dorsal) stream cortical networks. Growing evidence from neuroimaging studies supports this suggestion (Ding et al., 2013; Lerner et al., 2006; Li et al., 2007, 2011; Secen et al., 2001; for recent reviews, see Vida et al., 2012; Wong, 2012).

Nodes that are commonly implicated in these higher level dysfunctions include binocular regions of posterior parietal cortex, also generally associated with the programming and guidance of visually-guided actions (for recent review, see Goodale, 2011). Indeed, commensurate with this, a history of amblyopia and abnormal binocularity in both children and adults has recently been associated with slow and inaccurate performance, compared to matched developmentally-normal subjects, on a variety of everyday tasks requiring fine visuomotor control (for recent reviews, see Birch, 2013; Grant & Moseley, 2011; Wong, 2012). Of immediate relevance to the present study, specific performance deficits in relatively simple manual pointing (Niechwiej-Szwedo et al., 2011a, 2011b, 2012a, 2012b, 2014) or reach-to-precision grasping actions (Grant et al., 2007, 2014; Melmoth et al., 2009; Suttle et al., 2011) have been shown to include: (i) increased movement onset (i.e., planning/programming) times; and (ii) prolonged movement durations; mainly due to (iii) longer periods spent in the initial programmed phase of the movement (e.g., up to peak reach velocity or peak grip opening); with (iv) more corrections to the reach trajectory or digit positions during the later approach to the target; yet (v) terminating in more errors and loss of end-point accuracy. These deficits occur with habitual (i.e., both eyes open) and with amblyopic eye viewing, and even when using the dominant eye alone for some parameters mainly related to movement planning/programming. Moreover, their severity across all the 3 possible views – as on other fine visuomotor tasks (see Birch, 2013; Grant & Moseley, 2011) – usually correlates more with the patients' degree of binocular dysfunction than their visual acuity loss. It has been concluded from this that the defective binocular vision in amblyopia results in two general problems for motor control. First, it creates 'uncertainties' when attempting to encode the 3D spatial location and form/contour of target objects during movement planning, leading to impaired selection and programming of the hand actions directed towards them. Second, it impairs the use of subsequent visual feedback to correct these motor errors when attempting to guide the hand accurately to the target during movement execution.

By the term 'relatively simple' above, we mean that the deficits were revealed on tasks conducted under bright lighting with the hand directed to highly visible targets presented in structured environments containing many potential cues to distance and depth. However, in daily life, we are often required to interact with objects of low contrast relative to the background or in environments of low ambient illumination. Such low visibility situations have been shown to be more challenging for hand action control in normally-sighted adults (Churchill et al., 2000; Melmoth & Grant, 2012), resulting in slower movements accompanied by reduced end-point accuracy, analogous to the performance deficits of amblyopic adults under 'standard' high contrast conditions. Pardhan, Gonzalez-Alvarez, and Subramanian (2012) have also recently compared the performance during habitual viewing of older patients with marked central visual impairment affecting both eyes to that of age-matched controls on reach-to-precision grasps of high contrast *versus* low contrast or transparent 3D objects. The patients had prolonged movement onsets and durations, due to increased times to peak reach velocity and in grip closure during the guidance period, for the high contrast targets, and these indices of poorer performance were exacerbated – that is, deteriorated significantly more than in the controls – when the objects were of lower visibility. Reductions in binocular contrast sensitivity were more implicated in these effects than reduced visual acuity.

Against this background, we hypothesized that the greater demands imposed on the amblyopic visual system for encoding objects with low contrast or visibility would likely result in a similar exacerbation of their problems in hand action planning/programming and in error generation. More specifically, we predicted that their deficits in all aspects of movement timing and accuracy outlined above for high contrast objects should deteriorate much more on these harder tasks under all viewing conditions compared to the performance of control subjects, with the effects probably being more evident in non-binocular amblyopes with markedly reduced contrast sensitivity. The present study represents a preliminary test of these hypotheses, conducted on a sample of adult patients exhibiting a range of losses along the major dimensions of visual acuity, contrast sensitivity and binocularity.

2. Materials and methods

2.1. Participants

Twenty-six adult subjects took part in the study; 13 had a history of amblyopia and 13 were visually normal controls, matched by age (median = 23 years), gender (4 males, 9 females), sighting eye-dominance (6 right, 7 left) and hand-preference (12 right-handed patients, 11 right-handed controls), this latter information obtained from their responses to the short version of the Edinburgh inventory questionnaire (Oldfield, 1971). Participants were screened using standard clinical tests of (log MAR) visual acuity (VA), contrast sensitivity (CS), and binocularity, during which they wore any habitual refractive correction. VA was tested with both eyes open and with just the dominant (fellow/fixing/sighting) eye and non-dominant (affected/amblyopic/non-sighting) eye alone using a Bailey–Lovie chart held at 6 m. CS, at a spatial frequency corresponding to ~1 cycle per degree (cpd), was also measured under each of these 3 views using the Pelli–Robson chart at a distance of 1 m and test luminance ~64 cd/m^2. Assessments of binocularity included for suppression (Bagolini lenses); ocular alignment and motor fusion (cover test and prism fusion range); and stereo acuity (Wirt–Titmus test). All subjects gave informed consent to participate in the experiments, which were conducted in accord with the Declaration of Helsinki and with City University London ethical approval.

2.1.1. The subject's vision

Control subjects had no ocular disorders, other than refractive errors, and normal binocularity, with crossed stereo thresholds of at least 40 arcsec. Their average binocular, dominant eye and non-dominant eye log MAR VA was −0.14 (±0.09 sd), −0.07 (±0.14) and −0.03 (±0.14), respectively, with mean contrast sensitivities of 1.84 (±0.10), 1.71 (±0.08) and 1.71 (±0.09) under each of the 3 respective views. These latter are all at the lower end of normative values expected for adults in the age range (19–48 years) of our control participants (Mäntyjärvi & Laitinen, 2001). The likely explanation for this is that the luminance of the Pelli–Robson chart used was adapted to match to the normal lighting conditions of the hand movement testing laboratory (see below) and so was lower than that typically used in more formal clinical settings.

As summarized in Table 1, the amblyopia subjects comprised 6 with strabismus and 7 of mixed type (for 3 of whom – cases M3, M6, M7 – image degradation had probably been the main amblyogenic factor), but with the two sub-groups having similar distributions of visual loss along each of the 3 major dimensions. Average