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Sensitivity to synchronicity of biological motion in normal and amblyopic vision

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ABSTRACT

Amblyopia is a developmental disorder of spatial vision that results from abnormal early visual experience usually due to the presence of strabismus, anisometropia, or both strabismus and anisometropia. Amblyopia results in a range of visual deficits that cannot be corrected by optics because the deficits reflect neural abnormalities. Biological motion refers to the motion patterns of living organisms, and is normally displayed as points of lights positioned at the major joints of the body. In this experiment, our goal was twofold. We wished to examine whether the human visual system in people with amblyopia retained the higher-level processing capabilities to extract visual information from the synchronized actions of others, therefore retaining the ability to detect biological motion. Specifically, we wanted to determine if the synchronized interaction of two agents performing a dancing routine allowed the amblyopic observer to use the actions of one agent to predict the expected actions of a second agent. We also wished to establish whether synchronicity sensitivity (detection of synchronized versus desynchronized interactions) is impaired in amblyopic observers relative to normal observers. The two aims are differentiated in that the first aim looks at whether synchronized actions result in improved expected action predictions while the second aim quantitatively compares synchronicity sensitivity, or the ratio of desynchronized to synchronized detection sensitivities, to determine if there is a difference between normal and amblyopic observers. Our results show that the ability to detect biological motion requires more samples in both eyes of amblyopes than in normal control observers. The increased sample threshold is not the result of low-level losses but may reflect losses in feature integration due to undersampling in the amblyopic visual system. However, like normal observers, amblyopes are more sensitive to synchronized versus desynchronized interactions, indicating that higher-level processing of biological motion remains intact. We also found no impairment in synchronicity sensitivity in the amblyopic visual system relative to the normal visual system. Since there is no impairment in synchronicity sensitivity in either the non-amblyopic or amblyopic eye of amblyopes, our results suggest that the higher order processing of biological motion is intact.

1. Introduction

Amblyopia is a developmental disorder of spatial vision that results from abnormal early visual experience usually due to the presence of strabismus (an eye turn), anisometropia (a significant and unequal refractive error between the two eyes), or both strabismus and anisometropia (Ciuffreda, Levi, & Selenow, 1991; Levi, 1991; Levi & Carkeet, 1993). Amblyopia results in unilateral visual deficits, without apparent pathology, that cannot be corrected by optics because the deficits reflect neural abnormalities (Kiorpes, 2006; Levi, 2006). The most frequent cause of vision loss in infants and young children, aside from refractive error, amblyopia is clinically diagnosed as a reduction in visual acuity (Ciuffreda, Levi, & Selenow, 1991). In addition, for both types of amblyopia, strabismic and anisometropic, the amblyopic eye exhibits a marked loss of contrast sensitivity (Bradley & Freeman, 1981; Hess & Howell, 1977; Levi & Harwerth, 1977), an increased extent of spatial interference (Levi & Klein, 1985), and deficits in spatial localization (Hess & Holliday, 1992).

Amblyopic neural deficits first appear in the primary visual cortex, V1 (Kiorpes, 2006; Kiorpes & McKee, 1999). More recent studies have reported these amblyopic neural deficits may extend into extrastriate cortical areas (Aaen-Stockdale, Ledgeway, & Hess, 2007; Lerner et al., 2003, 2006; Simmers et al., 2003; Wong, Levi, & McGraw, 2001), and perhaps beyond (Sharma, Levi, & Klein, 2000). And a recent MRI study has found that the LGN may also be affected by amblyopia (Li et al., 2011). However, it is unclear whether these extrastriate cortical regions serve to amplify the losses that occur in V1, or if the downstream losses are simply the reflection of the original losses in V1. Previous studies have demonstrated that higher-

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level visual processing such as for biological motion, a complex form of structure-from-motion representing human actions, is unaffected by amblyopia (Neri, Luu, & Levi, 2007).

Biological motion refers to the motion patterns of living organisms, and is normally displayed as points of lights positioned at the major joints of the body. Johansson was the first to use point-light displays to show the perception of biological motion (Johansson, 1973, 1976). Static point-light displays were found to provide no percept of a human agent. Only when the point-lights were in motion could they be organized into the percept of a human agent. Point-light displays carry a wealth of information that provide human observers with higher-order information, allowing the observer to identify the figure's gender (Barclay, Cutting, & Kozlowski, 1978; Cutting, Proffitt, & Kozlowski, 1978), emotional state (Dittrich et al., 1996), identity (Cutting & Kozlowski, 1977; Troje, Westhoff, & Lavrov, 2005), intentions (Bingham, 1987; Runeson & Frykholm, 1983), and even the category of action that the figure is performing (Dittrich, 1993). In this study, we used point-light displays generated from the trajectories of the major joints of two human agents performing a dancing routine (Neri, Luu, & Levi, 2006).

Previous studies investigating the effects of amblyopia on higher-level cognitive functions have found that biological motion detection as processed by global form from motion (Neri, Luu, & Levi, 2007) and local motion information (Thompson et al., 2008) is relatively unaffected. In human observers with normal vision, visual discrimination of a human agent is influenced by the presence of a second agent and by whether the two agents interact in a meaningful and synchronized way, such as during a dancing or fighting routine (Neri, Luu, & Levi, 2006). This kind of synchronized interaction allows the human observer to use the actions of one agent to predict the expected actions of a second agent.

In this study, our goal was twofold. We wished to examine whether the human visual system in people with amblyopia retained the higher-level processing capabilities to extract visual information from the synchronized actions of others, therefore retaining the ability to detect biological motion. Specifically, we wanted to determine if the synchronized interaction of two agents performing a dancing routine allowed the amblyopic observer to use the actions of one agent to predict the expected actions of a second agent. We also wished to establish whether synchronicity sensitivity (detection of synchronized versus desynchronized interactions) is impaired in amblyopic observers relative to normal observers. The two aims are differentiated in that the first aim looks at whether synchronized actions result in improved expected action predictions while the second aim quantitatively compares synchronicity sensitivity, or the ratio of desynchronized to synchronized detection sensitivities, to determine if there is a difference between normal and amblyopic observers.

There is reason to suspect that synchronicity sensitivity may be impaired in amblyopic observers. The synchronous firing of spatially separate neurons is thought to be involved in the temporal processing of visual information (Asper, Crewther, & Crewther, 2000; Engel, Konig, & Singer, 1991; Roelfsema et al., 1994; but see Shadlen & Movshon, 1999 for a different view). However, the synchronicity of firing is reduced in cortical neurons driven by the amblyopic eye of strabismic cats, in comparison to the synchronous firing in both eyes of normal cats and the non-amblyopic eyes of strabismic cats (Roelfsema et al., 1994). Moreover, previous studies have reported that spatio-temporal processing may be impaired in humans with amblyopia (Asper, Crewther, & Crewther, 2000; Popple & Levi, 2008). These findings suggest that since synchronization of neural firing may be impaired in the amblyopic eye, synchronicity sensitivity will also be impaired in the amblyopic eye.

Our results show that the ability to detect biological motion requires more samples (dot trajectories) in both eyes of amblyopes than in normal control observers. The increased sample threshold is not the result of low-level losses (dot trajectories were highly visible) but may reflect losses in feature integration due to undersampling in the amblyopic visual system (Levi & Klein, 1986; Levi, Klein, & Sharma, 1999; Levi, Klein, & Yap, 1987). However, like normal observers, amblyopes are more sensitive to synchronized versus desynchronized interactions, indicating that higher-level processing of biological motion remains intact, as previously reported (Neri, Luu, & Levi, 2007; Thompson et al., 2008). Similar to normal vision, in amblyopia the difference in biological motion perception between synchronized and desynchronized stimuli is due to the disruptive effect of desynchronization on the perception of biological motion. We also found no impairment in synchronicity sensitivity in the amblyopic visual system relative to the normal visual system. This suggests that higher order processing of biological motion remains intact in the amblyopic visual system.

2. Material and methods

2.1. Observers

Seven amblyopic observers participated in our study (see Table 1 for the visual characteristics of these observers). Of the seven amblyopic observers, three were strabismic (SS1–SS3), two were both strabismic and anisometropic (SB1 and SB2), and two were anisometropic (SA1 and SA2). In the figures, the amblyopic results are colored according to the type of amblyopia (strabismic – red; strabismic and anisometropic – blue; non-strabismic anisometropic – green). All amblyopic observers wore their best optical correction when performing the study. Five observers with normal, or corrected to normal, visual acuity and stereoacuity participated as controls in our study. All observers, except for one author, were naïve observers.

2.2. Motion capture

A routine by two dancers (recruited from the UC Berkeley Ballroom Dancers) performing the Rumba was filmed using a camera device (Logitech QuickCam) that generated digital AVI movies at 10 Hz and 640 × 480 pixel resolution (Fig. 1). Each dancer was outfitted with clothing that carried battery-powered wire light markers (ClubThings, Los Angeles, CA) positioned at 13 points on the body: one at the head, and one at each shoulder, elbow, wrist, hip, knee, and ankle. We created customized Matlab software to aid in the movie processing and to provide computer-assisted motion capture. The software used basic clustering analysis to detect regions of high luminance on the body of each dancer to determine the positions of the light markers. The trajectories of these markers were then tracked through each frame of the movie. A graphic user interface included in this software allowed the user to view the automated tracking frame-by-frame and make corrections when needed to correct the numerous errors made in the automated process. This user interface allowed for the tracking of the full trajectories of the 13 major joints on each dancer in x–y–t space (the sequence was interpolated to obtain 30 Hz sampling), and allowed for the marking of joint disappearances due to occlusion. The final tracked dancing routine was 24 s in length.

2.3. Stimuli

The trials in this experiment were of either 'Sync' or 'Desync' type. Sync and Desync trials were randomly presented within a block, and in each trial both intervals were either Sync or Desync. Sync trials consisted of a short segment randomly selected from the two sequences that result from the first and second halves of the original tracked movie (Fig. 2A and B). Desync trials consisted