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Optimal Audiovisual Integration in People with One Eye

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Abstract

People with one eye show altered sensory processing. Such changes might reflect a central re-weighting of sensory information that might impact on how multisensory cues are integrated. We assessed whether people who lost an eye early in life differ from controls with respect to audiovisual integration. In order to quantify the relative weightings assigned to each sensory system, participants were asked to spatially localize audiovisual events that have been previously shown to be optimally combined and perceptually fused from the point of view of location in a normal population, where the auditory and visual components were spatially disparate. There was no difference in the variability of localizing unimodal visual and auditory targets by people with one eye compared to controls. People with one eye did however, demonstrate slower reaction times to localize visual stimuli compared to auditory stimuli and were slower than binocular and eye-patched control groups. When localizing bimodal targets, the weightings assigned to each sensory modality in both people with one eye and controls were predictable from their unimodal performance, in accordance with Maximum Likelihood Estimation and the time it took all three groups to localize the bimodal targets was faster than for vision alone. Regardless of demonstrating a longer response time to visual stimuli, people with one eye appear to integrate the auditory and visual components of multisensory events optimally when determining spatial location.

Keywords

Auditory, visual, multisensory, monocular, binocular, enucleation

1. Introduction

It is a common popular notion that losing vision results in an enhanced ability to use the other senses. Hollywood has encouraged this idea in a number of movies where blind people are portrayed as having a heightened sense of

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touch ("At First Sight", 1999), smell ("Profumo Di Donna", 1974) or hearing ("Daredevil", 2003). Indeed, empirical evidence exists showing cross-modal plasticity in the form of better hearing in the early blind (e.g., sound localization: Lessard *et al.*, 1998) and that previously visual areas of the brain are taken over by other senses such as touch (Röder *et al.*, 2002). Complete blindness is a relatively rare condition, however, and disorders of binocularity leading to monocular impairment such as strabismus and amblyopia are far more common with a prevalence estimated at approximately 10% of the population. A unique form of monocular impairment is unilateral eye enucleation, where one eye is surgically removed resulting in a complete deafferentation of one half of visual input to the brain. It is possible that people who have had an eye removed early in life have altered processing in their remaining senses similar to what has been documented in the early blind. People with one eye may alter the way they are able to integrate information across the senses due to a similar recruitment of visual areas by other sensory systems that has been demonstrated in complete blindness.

Monocular enucleation as a form of visual deprivation provides a unique model for studying and understanding the underlying neural consequences of the loss of binocularity commencing early in life. Unlike complete blindness, monocular enucleation allows us to examine the interplay between the senses since vision has not been completely eliminated. Moreover, monocular enucleation differs from other more common forms of monocular deprivation such as strabismus and amblyopia since it does not leave anomalous visual signals to the brain from the deprived eye. As a result, monocular enucleation provides a 'clean' model of the effects of changing sensory input to the brain on vision itself and on the remaining senses.

Unlike monocular deprivation from strabismus, amblyopia, or congenital cataract early in life which produce a number negative effects on visual function and the underlying neural substrates (e.g., Hess *et al.*, 1999; Ho *et al.*, 2005; Lewis *et al.*, 2002; for developmental reviews see Atkinson, 2000; Daw, 2006), early monocular deprivation from eye enucleation shows a different pattern of results — one that is less adverse than other forms of monocular deprivation. This is surprising considering that eye enucleation is a significant alteration to the visual system since the visual system has evolved to receive input through two eyes in its intact and mature state. There are at least three immediate and severe changes to the visual system. First, losing one eye decreases by half the physical light input to our visual system compared to the intact binocular visual system. This in turn eliminates probability summation and neural summation of visual inputs. Second, the visible visual field is reduced horizontally by about 25% on the side of the non-functional eye displacing the available visual field towards the intact eye rather than centered on the midline of the body. Third, having only one eye eliminates the powerful

binocular depth cue, stereopsis, which arises from retinal disparities between the two eyes.

Losing a sensory system can alter the way the remaining sensory systems are used by the brain (Röder *et al.*, 2002). Given that the environment does not consist of unisensory stimuli but rather a host of information is delivered through the multiple senses, the integration of multiple sensory cues can substantially improve both the accuracy and precision of perception. What these sensory cues are and how important each cue is in particular tasks has been studied extensively (e.g., Alais *et al.*, 2010; Battaglia *et al.*, 2003; Bertelson and Aschersleben, 1998; Welch and Warren, 1980; see Stein, 2012 for a review). There is ample evidence that the visual system changes in response to the loss of one eye and some evidence that hearing is altered in response to this compromised visual system. People who have lost an eye early in life have shown enhanced visual spatial form ability such as increased contrast sensitivity (Nicholas *et al.*, 1996) but reduced visual motion processing (see Kelly *et al.*, 2012; Steeves *et al.*, 2008 for reviews). Cross-modal adaptations have also been demonstrated in people with one eye who show enhanced auditory localization in the horizontal azimuth and do not show the typical tendency to mislocalize sounds towards the visual midline compared to controls (Hoover *et al.*, 2012). Further, the enhancement in sound localization is not restricted to the blind portion of the visual field following monocular enucleation. Moreover, people with one eye do not show the typical pattern of visual dominance when asked to categorize quickly presented audiovisual targets (Colavita visual dominance effect; Colavita, 1974) but rather show equivalent auditory and visual processing suggesting an enhanced weight being applied to the auditory component of a bimodal stimulus (Moro and Steeves, 2012). However, the Colavita task typically does not require 'fusion' of the auditory and visual components and hence does not require multisensory integration. These examples of processing differences have been found in unimodal auditory and visual processing in people with one eye, however to date, no studies have investigated bimodal audiovisual spatial processing in this group. It is possible that sensory integration processes are altered with the altered input to the visual system following early monocular enucleation.

In order to measure sensory weighting in an integration task we used the classic ventriloquism illusion. When people are presented with paired auditory and visual stimuli that appear to originate from a single event, a single fused perceptual event is often perceived (Welch and Warren, 1980). When the components of an audiovisual stimulus are displaced relative to one another in space it results in the perception of a single event usually spatially displaced towards the visual component. This illusory percept, called the ventriloquism effect, demonstrates the typical visual over auditory dominance in spatial tasks (Alais *et al.*, 2010; Bertelson and Aschersleben, 1998; Welch and

Warren, 1980). However, the true integrative nature of this effect can be revealed by "leveling the playing field" in order to reduce the reliability of the typically dominant visual cue to localization until it is as reliable as that for the auditory cue (Alais and Burr, 2004). This can be achieved by blurring a visual image to reduce its visual spatial location reliability to equate its reliability to that for auditory spatial location. The perceived location of audiovisual events can be accurately predicted from the reliability of each component measured alone, according to Maximum Likelihood Estimation (MLE) confirming statistically optimal integration (Alais and Burr, 2004).

We ask whether people with one eye integrate audiovisual stimuli along the horizontal azimuth differently from controls. We used the classic ventriloquism paradigm developed by Alais and Burr (2004) as the gold standard assessment of the sensory integration process.

2. Methods

2.1. Participants

2.1.1. People with One Eye (ME)

Six participants who had undergone monocular enucleation (ME) at a clinic at The Hospital For Sick Children participated in all the experiments (mean age = 29.3 years, SD = 10.5, 3 female). All participants with one eye (ME) had been unilaterally eye enucleated due to retinoblastoma, a rare childhood cancer of the retina (four participants with right eye removed, two participants with left eye removed). Age at enucleation ranged from 4 months to 26 months (mean age = 16 months, SD = 7.2).

2.1.2. Control Participants (BV and MV)

Six binocularly intact participants, with a mean age of 28.3 years (SD = 6.8, four female), completed the experiments in counterbalanced order, as a control in both binocular (BV) and eye-patched monocular viewing (MV) conditions. In the eye-patched condition the participants' non-preferred eye was patched with a semi-opaque eye covering and translucent tape (two right-eye covered).

All participants (ME, BV and MV) reported normal hearing and normal or corrected-to-normal Snellen acuity (Precision Vision, La Salle, IL, USA) and wore optical correction if needed. All participants gave informed consent prior to their inclusion in the study and all studies were approved by York University Office of Research Ethics and were conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki.

2.2. Stimuli

Visual stimuli consisted of low contrast (10%) 20° Gaussian blobs, back-projected by a Hitachi CP-X505 Multimedia LCD projector onto a 90 cm ×

120 cm screen for 15 ms. Blob size was selected based on the results of Alais and Burr (2004). Auditory stimuli were brief 1.5 ms clicks presented through two visible speakers at the edges of the screen (separated by 67°). The apparent position of the sound was controlled by manipulating the interaural time difference from 0 to ±800 μs corresponding to a displacement of 32° to −32°. Interaural time differences were based on a generic head model and applied to all participants. All stimuli were presented using VPixx stimulus presentation software and DATAPixx hardware for precise stimulus timing (VPixx Technologies Inc., www.vpixx.com).

2.3. Procedure

Participants sat 60 cm from the screen in a dimly lit testing room. In all experiments, each trial consisted of two intervals with either unimodal auditory, unimodal visual, or bimodal (audiovisual) stimuli (see Fig. 1). Stimulus presentations (see below) were separated by an interval of 500 ms. Participants were asked to indicate, using a keyboard, as quickly and accurately as possible whether the first or second stimulus interval was perceived more to the left. Conditions were run using a counterbalanced block design with blocks of either unimodal auditory trials, unimodal visual trials or bimodal trials. A short practice session was included at the beginning of each run to familiarize participants with the task.

The unimodal conditions consisted of one stimulus (either auditory or visual) presented near the center (with a small jitter of ±0.5°) and a second presentation displaced either to the left or right (auditory ±32° in 2° steps, visual ±16° in 2° steps) separated by a 500 ms interstimulus interval of silence and a blank screen. There were 20 presentations at each of the seventeen visual eccentricities for a total of 340 trials, and eight presentations at each of the 34 auditory stimulus positions for a total of 272 trials.

For the bimodal condition participants were instructed to make judgments about the perceived position of an audiovisual event. All bimodal trials comprised two stimulus intervals that were presented in random order separated by a 500 ms interstimulus interval of silence and a blank screen. In one interval the visual and auditory stimuli were at the same central location while in the other the visual and auditory stimuli were displaced relative to each other around a position that could be at various eccentricities (that is, the two components indicated different locations of the bimodal stimulus: 'conflict') (similar to Alais and Burr, 2004). For some of the trials the relative displacement of the components was zero producing a "non-conflict bimodal condition". For each trial, participants were asked to indicate in which interval the stimuli appeared more leftward. In the 'non-conflict' interval, the auditory and visual information were paired together in the same spatial location at seventeen positions (±16° in 2° steps) with 20 repetitions for a total of 340 trials. In the 'conflict'

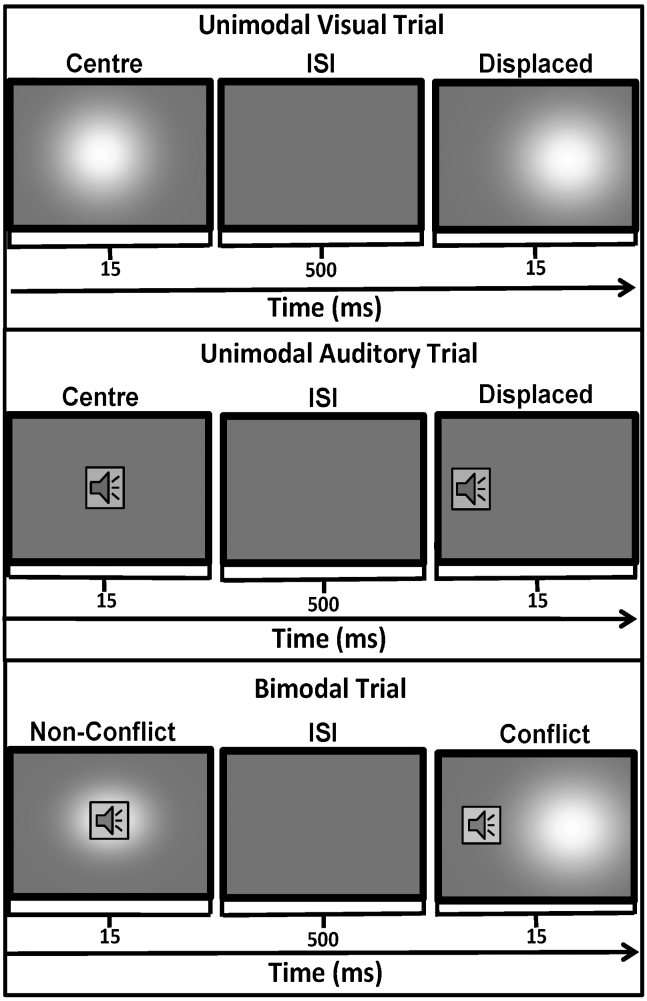

Figure 1. A schematic illustration of the stimulus timeline for each trial type. Participants were asked to indicate in which of the two intervals the stimulus appeared more leftward. Unimodal visual, unimodal auditory and bimodal trials were presented in separate blocks.

interval, the visual and the auditory information were presented at the same time but the visual stimulus was displaced horizontally by a designated distance ($\Delta°$) and the auditory stimulus displaced in the opposite direction by the same designated distance ($\Delta°$) either: ± 2.5 and $\pm 5°$, i.e., for combinations, each centered on one of the seventeen positions. There were 20 presentations at each of the four $\Delta°$s at each of the eccentricities for a total of 1360 trials. The order of trials within a condition was randomized and the order of the unimodal and bimodal conditions were counterbalanced across participants.

2.4. Measuring Response Latencies

Response latencies were measured for each trial. Timing began upon stimulus offset. Response latencies were recorded when participants made a response. Trials were self-paced. Participants were instructed to respond as quickly and as accurately as possible.

2.5. Data Analysis

All data were plotted as the proportion 'perceived left' as a function of the overall displacement of the stimuli. Data were fit with a cumulative Gaussian psychometric function. For tests that did not satisfy the normality assumption post hoc tests were conducted using the appropriate non-parametric Mann–Whitney U Test. For tests where the assumption of sphericity was violated a Greenhouse–Geisser correction was used.

3. Results

3.1. Variance of Unimodal Stimuli

The proportion of unimodal auditory and visual stimuli perceived as more leftward relative to the centrally presented stimulus for a typical control participant viewing binocularly (BV) or with one eye patched (MV), as well as, a typical person with one eye (ME) are plotted as a function of physical displacement in Fig. 2. The variance was calculated from the best-fit cumulative Gaussian psychometric functions. The points of subjective equality (PSEs) for this experiment were all located centrally. A 2 × 3 mixed design Analysis of Variance (ANOVA) comparing mean variance for Modality (auditory and visual) as a function of Participant Group revealed no significant interaction [$F(2, 15) = 0.113$, $p = 0.89$; $\eta_p^2 = 0.015$]. This indicates that the auditory and visual variance did not differ between participant groups. Bonferroni post hoc comparisons indicate that the auditory and visual variance for people with one eye did not differ from eye-patched controls ($p > 0.05$) or binocular controls ($p > 0.05$).

3.2. Variance of Bimodal Stimuli

The proportion of bimodal trials perceived leftward at each conflict condition for the same participants is illustrated in Fig. 2 and plotted in Fig. 3a. The variance and perceived location is calculated from the cumulative Gaussian psychometric functions fit to the data. A 3 × 5 mixed design ANOVA comparing mean variance for Participant Group as a function of Stimulus Displacement (no conflict and conflicts of ±2.5° and ±5°) revealed no significant interaction [$F(8, 60) = 1.372$, $p = 0.26$; $\eta_p^2 = 0.155$].

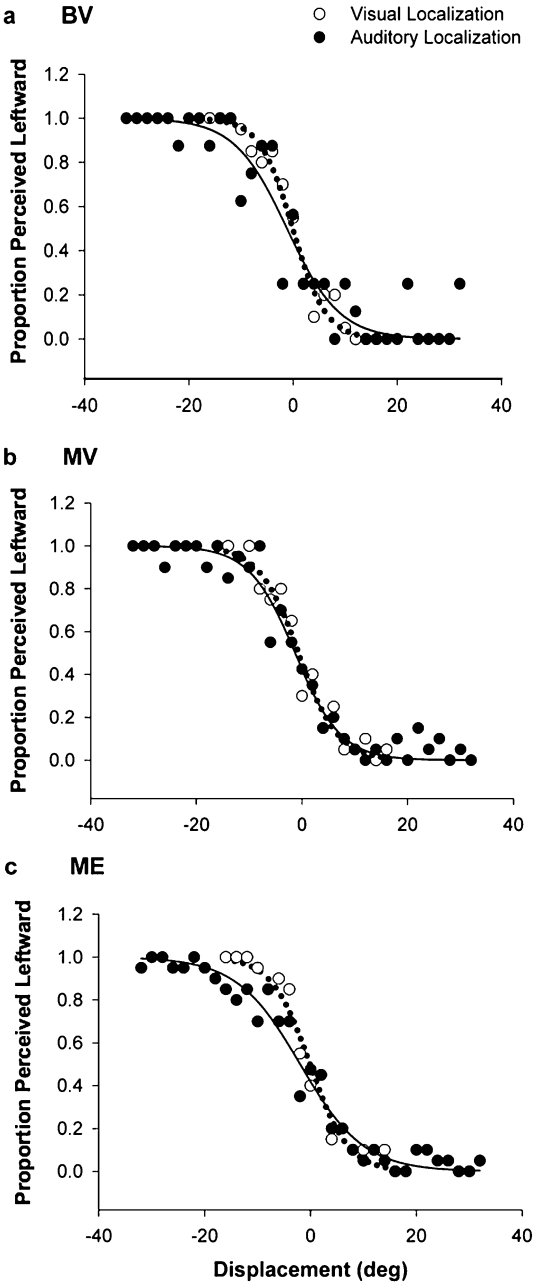

Figure 2. Typical examples of the proportion perceived left of center of unimodal auditory (filled circles) and visual (open circles) stimuli plotted as a function of displacement. (a) A control participant viewing binocularly (BV); (b) the same control participant with one eye patched (MV) and (c) a person with one eye (ME). The lines fit through the data are best-fit cumulative Gaussian psychometric functions (auditory solid, visual dotted).

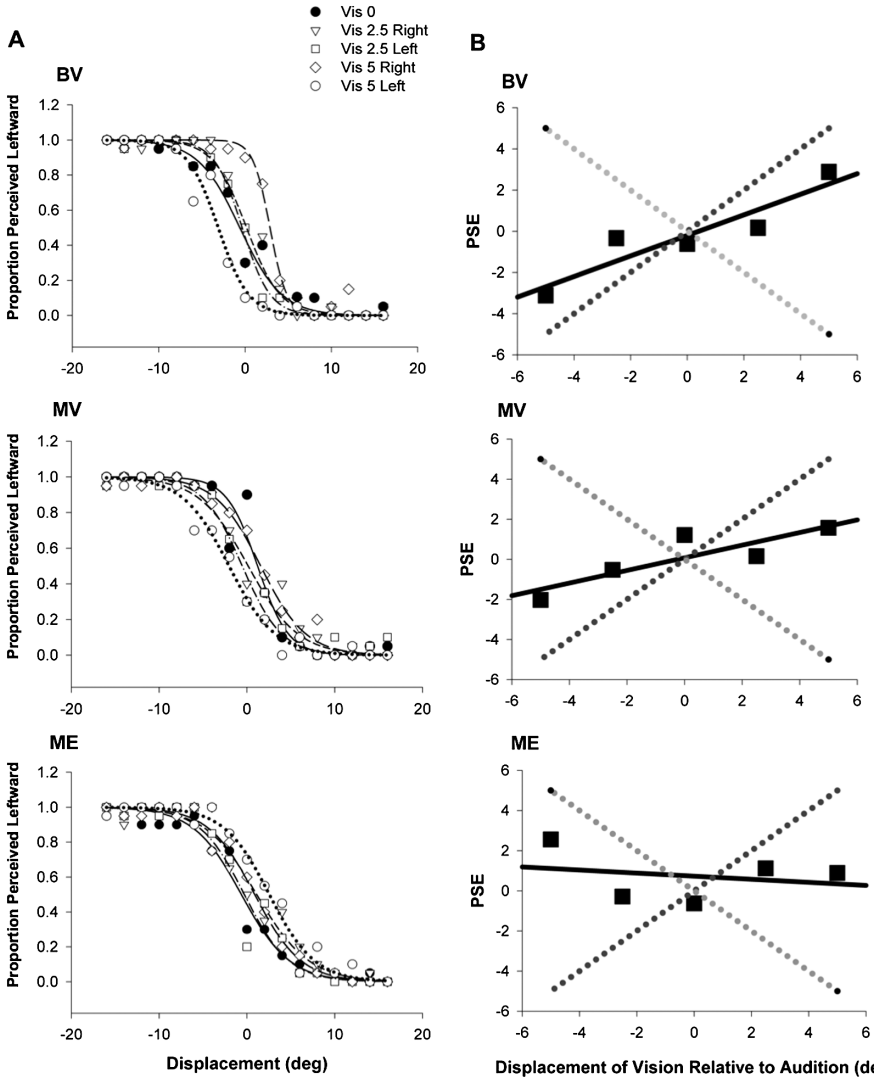

Figure 3. (A) Proportion of bimodal trials localized left of the central reference stimulus for each conflict condition for a typical control participant viewing binocularly (BV) and with one eye patched (MV), and a person with one eye (ME) plotted as a function of displacement. The lines fit through the data are cumulative Gaussian psychometric functions (see methods). 0° displacement: filled circle and solid line, visual displacement 2.5° to the right: open triangle and short dashed line, visual displacement 2.5° to the left: open square and dash-dot line, visual displacement 5° to the right: open diamond and long dash line, visual displacement 5° to the left: open circle and dotted line. (B) Plot of the PSE as a function of the visual displacement of the conflicting stimuli for the same participants shown in (A). A linear regression line is plotted for each graph (solid line). A slope of 1 would indicate that the participant followed the visual component exclusively (visual dominance, dark grey dotted line) while a slope of −1 would indicate auditory dominance (light grey dotted line) (see text).

3.3. Perceived Location of Bimodal Stimuli

The PSE for each psychometric function is where the participant perceived the stimulus to be presented centrally (i.e., equally likely to be perceived left or right of center). Figure 3b plots the PSE as a function of the conflict conditions for the accompanying typical participants illustrated in Fig. 3a. Regression lines were plotted through the data to determine any shift in PSE as a function of conflict. A slope of +1 (dotted black line in Fig. 3b) would indicate that the responses were completely dominated by vision and that judgments were based solely on the position of the visual component of the bimodal stimulus; a slope of −1 (dotted grey line in Fig. 3b) would indicate that judgments were based solely on the auditory component. A one-way ANOVA compared the slope of these regression lines across Participant Group. There was no significant interaction [$F(2, 18) = 0.332$, $p = 0.57$; $\eta_p^2 = 0.022$] between slope and Participant Group. This indicates that the mean PSE slope for all participant groups did not significantly differ from each other.

3.4. Response Latency of Unimodal and Bimodal Stimuli

The response time was measured for each subject in each condition. A 5 (Stimulus Displacement) × 3 (Participant Group) mixed design Analysis of Variance (ANOVA) was performed on bimodal response latencies with Participant Group as the between subjects factor and Stimulus Displacement as the within-subjects factor. There was a main effect of Participant Group [$F(2, 15) = 5.173$, $p = 0.02$; $\eta_p^2 = 0.408$]. There was no main effect of Stimulus Displacement [$F(4, 60) = 2.410$, $p = 0.11$; $\eta_p^2 = 0.138$]. Given that there was no difference between bimodal conditions within each participant group we collapsed across the different bimodal displacement positions. A 3 (Modality) × 3 (Participant Group) mixed design ANOVA was performed comparing response latencies with the Participant Group as the between subjects factor and Modality (visual, audition and collapsed bimodal) as the within-subjects factor. There was a main effect of Participant Group [$F(2, 15) = 4.789$, $p = 0.025$; $\eta_p^2 = 0.390$] and Modality [$F(2, 30) = 37.08$, $p < 0001$; $\eta_p^2 = 0.712$]. All participants responded faster to bimodal stimuli compared to unimodal auditory and unimodal visual stimuli. Specifically, bimodal response latencies were fastest for all groups followed by audition and then vision indicating intersensory facilitation. Bonferroni corrected post-hoc tests showed that people with one eye responded significantly slower when localizing visual (BV: $p = 0.037$; MV: $p = 0.007$) and bimodal (BV: $p = 0.029$; MV: $p = 0.037$) stimuli compared to binocular and eye-patched controls. People with one eye did not differ from either control group when responding to auditory stimuli. Furthermore, vision was significantly slower compared to bimodal but not auditory localization for binocular ($p < 0.01$) and eye-patched ($p = 0.01$)

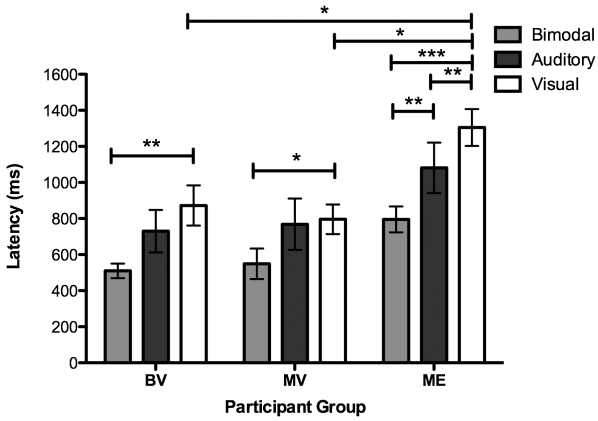

Figure 4. Response latency for unimodal and bimodal (collapsed across displacement condition) localization for control participants viewing binocularly (BV) and with one eye patched (MV), and people with one eye (ME). Error bars indicate Standard Errors. Asterisks show significant differences at the $p < 0.05$ (*), 0.01 (**) and 0.001 (***) levels.

controls. People with one eye also responded significantly more slowly on visual localization (1305 ms) compared to auditory localization (1081 ms) ($p = 0.040$) and both of these unimodal latencies were slower than those for bimodal trials (vis: $p < 0.001$; aud: $p = 0.018$). Figure 4 illustrates the mean response latencies for auditory and visual localization for each group.

3.5. Modeling the Data

The unimodal and bimodal variance (Fig. 2) and the relative weighting assigned to the visual and auditory components of the bimodal stimuli was used to test whether each group, in particular people with one eye, demonstrates optimal integration in this task using the prediction of the Maximum Likelihood Estimation (MLE) model (Myung, 2003).

Predicted estimates of the perceived location of bimodal targets were calculated for each participant from the variance of the responses to each unimodal stimulus. The predicted weightings for audition (W_A) and vision (W_V) were obtained based on the assumption that weighting is inversely proportional to the variance (σ_V^2, σ_A^2) of each unimodal estimate (equation (1)).

$$W_A = \frac{\sigma_V^2}{\sigma_A^2 + \sigma_V^2}, \qquad W_V = \frac{\sigma_A^2}{\sigma_V^2 + \sigma_A^2}. \tag{1}$$

The ratio of weightings (W_V/W_A) obtained in this way for each subject was compared to the ratio of weights obtained experimentally from the slopes of the best-fit line generated by plotting the PSE shift for each bimodal conflict condition as a function of spatial displacement (Fig. 3b). The goodness of fit of these predictions is illustrated in Fig. 5 where each participant's slope of PSE

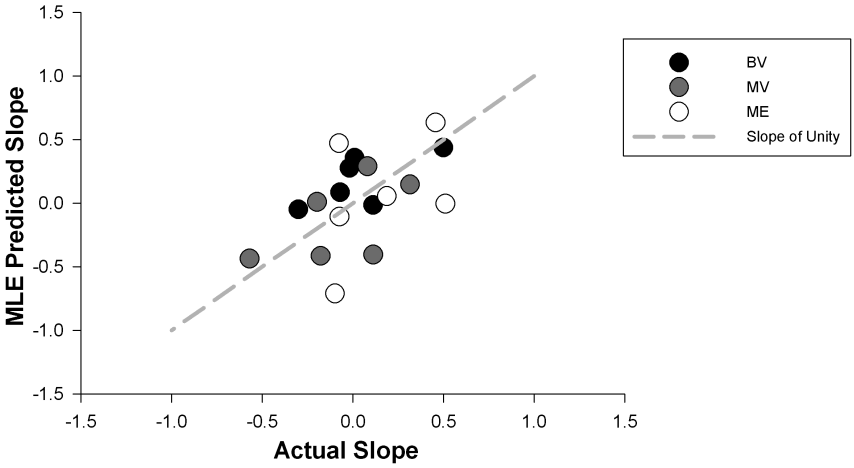

Figure 5. Actual versus predicted ratio of auditory and visual weightings (slopes — see results) for bimodal trials for each participant: Binocular (BV) controls (black circles); eye-patched (MV) controls (grey circles); and people with one eye (ME) (white circles). The grey dashed line represents a slope of unity for equal actual and predicted values.

is plotted as a function of the MLE prediction. A slope of 1 would indicate that the prediction was perfect. A one-way ANOVA of mean slope of PSE for each Participant Group revealed no significant difference [$F(2, 17) = 0.928$, $p = 0.417$; $\eta_p^2 = 0.110$]. This indicates that the predictions were as good for people with one eye as they were for both control groups. In other words, all groups performed optimally.

A further prediction of optimal integration is that the variance of the bimodal estimate will always be less than that for either of its unimodal components. This value can be predicted by equation (2) (Ernst and Banks, 2002).

$$\frac{1}{\sigma_{\mathrm{VAp}}^2} = \frac{1}{\sigma_{\mathrm{V}}^2} + \frac{1}{\sigma_{\mathrm{A}}^2}, \tag{2}$$

where σ_{V}^2 and σ_{A}^2 are the variances of the visual and auditory unimodal trials respectively and σ_{VAp}^2 is the predicted variance for the bimodal trials.

Figure 6 compares the average variance of unimodal and bimodal trials (collapsed across all the conflict displacement positions) with the predicted bimodal variance. For all participant groups, the bimodal variance was less than that for the unimodal auditory and visual conditions. A 4 (Condition) × 3 (Participant) ANOVA compared the actual and predicted estimations and showed no significant interaction [$F(4.02, 30.13) = 0.137$, $p = 0.97$; $\eta_p^2 = 0.018$; Greenhouse–Geisser corrected]. Bonferroni corrected pairwise comparisons revealed no significant difference between unimodal auditory and visual variance for all groups (ps > 0.05), indicating that, as intended by our choice of

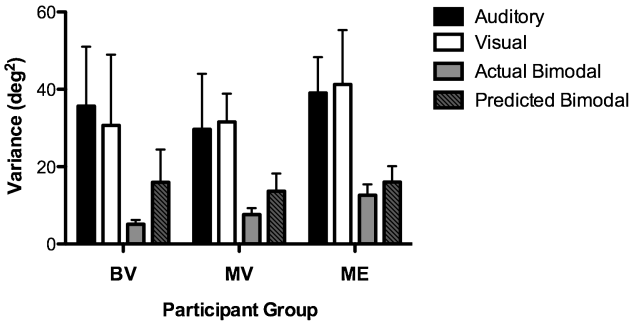

Figure 6. Variances for each participant group for all conditions and the bimodal variance predicted by Maximum Likelihood Estimation (see key insert). The bimodal variance is averaged across all conflict displacements. Error bars represent standard errors.

stimuli, auditory and visual variances were not significantly different for each group. No significant differences were found between the actual and predicted bimodal variance for any group (ps > 0.05), indicating that the MLE prediction was not significantly different from actual bimodal performance.

4. Discussion

The current study investigated audiovisual integration in people with one eye. Overall, people with one eye did not show a difference in variance of audiovisual localization compared to control groups viewing binocularly or with one eye patched. All participants, whether viewing binocularly, with one eye patched, or with only one eye showed no difference in any of the localization measures in the present study. This demonstrates that simply reducing the visual input to one eye, either by patching it or removing it altogether, does not affect audiovisual localization behavior. When examining participant response latencies all groups showed the same pattern: fastest reaction time for bimodal localization followed by unimodal auditory and visual localization. This sequence is consistent with intersensory facilitation (Sinnett *et al.*, 2008). However, unlike binocular and eye-patched controls, people with one eye took longer to localize unimodal visual stimuli compared to unimodal auditory stimuli. Moreover, their visual response latencies were significantly slower than those of either the binocular or eye-patched control groups. Nonetheless, like both control groups, people with one eye performed audiovisual localization optimally in accordance with the MLE model.

Here we have shown that people with one eye integrate auditory and visual information optimally despite the loss of half of the input to the visual system. Previously we had shown that they are more accurate at sound localization compared to controls (except in the extreme periphery) but show no difference in variance (Hoover *et al.*, 2012). It is possible that an advantage in unimodal

sound localization contributes to their ability to maintain normal *audiovisual* integration. Optimal sensory integration is an essential aspect of daily living, providing reliable information about the surrounding environment that can accurately be used to interact in the world (Myung, 2003).

4.1. Slower Response Latencies for People with One Eye

Despite demonstrating optimal integration, people with one eye took dramatically longer than controls to make localization judgments for visual compared to auditory stimuli (by 224 ms, see Fig. 4), a difference that was not observed in either binocular or eye-patched control groups. Moreover, people with one eye were also significantly slower at localizing unimodal visual stimuli compared to BV or MV (by 433 ms and 509 ms respectively). Nonetheless, this increase in reaction time for the visual modality did not affect overall localization performance for the people with one eye. We speculate that people with one eye may alter their ability to process visual information (resulting in slower reaction time) in order to achieve similar audiovisual localization performance compared to control groups. It is unclear whether this occurs at sensory or higher processing levels or perhaps a combination of both given the data on this patient population at this point. Neuroimaging data has recently shown that people who have lost one eye early in life have altered cortical and subcortical visual structures (see Kelly *et al.*, 2014). It is possible that changes in visual neural connectivity and morphology leads to slower visual processing time. Despite these changes to the visual system, slower processing time may not affect accuracy of visual behavior. The present data showing an increased response latency for visual stimuli compared to controls are consistent with data showing increased response latencies in people with one eye in a face perception and visual symmetry perception task in which they perform at the same level as controls but take significantly longer to do so (Cattaneo *et al.*, 2014; Kelly *et al.*, 2012).

4.2. Optimal Sensory Integration in People with One Eye

Consistent with the MLE and previously published data in binocular viewing controls (Alais and Burr, 2004) our results strongly support optimum combination of auditory and visual cues to spatial location in our patients and control groups. Based on evidence of cross-modal adaptations in previous studies of people with one eye, for example, enhanced auditory localization (Hoover *et al.*, 2012) and lack of visual dominance when categorizing audiovisual stimuli by modality (Moro and Steeves, 2012), these results are somewhat surprising. Since sensory integration depends on the relative weighting assigned to the component stimuli, we reasoned that a change in ‘dominance’ might be reflected in fundamental sensory integration processes. It is evident, however, that sensory integration is unaffected by the loss of one eye. Perhaps losing one

half of the visual input to the brain does not affect overall performance during audiovisual integration but any consequent cortical/subcortical reorganization may contribute to achieving normal performance in a different (i.e., slower) way through altered neural circuitry. It may be the case that other more common forms of monocular deprivation such as amblyopia or strabismus may also show a different pattern of audiovisual integration although there is little multisensory research in these patient groups to date.

4.3. Summary

Overall, regardless of the loss of half of the input to the visual system, people with one eye integrate auditory and visual information optimally, similar to controls. This is the first time multisensory integration has been tested in this population. The fact that they show normal integration, even if they seem to take longer to do so, opens the door to developing multisensory aids for this group — possibly using artificially created auditory signals to indicate visual events in the blind field, for example. It also supports the substantial effort to develop multisensory aids for the completely blind (e.g., Serino *et al.*, 2007).

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