LONG-TERM CONSEQUENCES OF EARLY EYE ENUCLEATION ON AUDIOVISUAL PROCESSING

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Abstract

A growing body of research shows that complete deprivation of the visual system from the loss of both eyes early in life results in changes in the remaining senses. Is the adaptive plasticity observed in the remaining intact senses also found in response to partial sensory deprivation – specifically, the loss of one eye early in life? My dissertation examines evidence of adaptive plasticity following the loss of one eye (unilateral enucleation) early in life. Unilateral eye enucleation is a unique model for examining the consequences of the loss of binocularity since the brain is completely deprived of all visual input from that eye. My dissertation expands our understanding of the long-term effects of losing one eye early in life on the development of audiovisual processing both behaviourally and in terms of the underlying neural representation. The over-arching goal is to better understand neural plasticity as a result of sensory deprivation. To achieve this I conducted seven experiments, divided into 5 experimental chapters, that focus on the behavioural and structural correlates of audiovisual perception in a unique group of adults who lost one eye in the first few years of life. Behavioural data (Chapters II-V) in conjunction with neuroimaging data (Chapter VI) relate structure and function of the auditory, visual and audiovisual systems in this rare patient group allowing a more refined understanding of cross sensory effects of early sensory deprivation. This information contributes to us better understanding how audiovisual information is experienced by people with one eye. This group can be used as a model to learn how to accommodate and maintain the health of less extreme forms of visual deprivation and to promote overall long-term visual health.

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Preface

"At a party in my honour, I volunteered to mix a martini for a thirsty young woman. I mixed it perfectly. Then, when she held up her glass to receive it, I poured it on the floor."

- Frank B. Brady, author of *A Singular View: The Art of Seeing with One* Eye (p. 6)

As Frank Brady describes in his book, when faced with living life with only one eye an individual will be exposed to persistent amounts of "jolts of reality" often involving awkward physical interactions disguised as clumsiness, due to the narrowing of the visual field by 20-40% and lack of stereoscopic (3D) depth perception. People with one eye can lead normal, active lives due to an array of compensatory behaviours. In fact, distinguished public figures such as US President Theodore Roosevelt, Sammy Davis Jr., and "Columbo" actor Peter Falk have made significant contributions to their fields' despite living life with only one eye.

This dissertation examines multisensory, specifically audiovisual, perception in people who have had one eye removed early in life, in an attempt to document the brain's reorganization abilities to compensate for the loss of one eye. This work contributes to a growing literature documenting the visual and multisensory abilities in people with one eye. Along with forthcoming research, understanding the behavior and underlying neural correlates of individuals with one eye may help inform the implementation of new adaptive behaviours that can be utilized by those with one eye, as well as individuals with less severe forms of monocular visual deprivation, such as cataract, strabismus, and amblyopia.

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CHAPTER I

GENERAL INTRODUCTION

As humans, we are a species with a number of active sensory systems. As we interact with our everyday world, we typically experience a combination of different sensory stimuli at the same time through several of our sensory systems. If all sensory systems are intact, we use them to our full advantage. When walking down a street, our vestibular and proprioceptive systems tell us about our body position and our olfactory system tells us about the odors from car exhaust and perfume of other pedestrians. Our auditory system tells us about the buzz of noise from the cars and people around us. Lastly, our visual system tells us what obstacles are in our path, the status of the traffic on the street and other important information about our surroundings. If visual input were reduced by half, as in the case of people with one eye, it seems reasonable to expect that the other intact sensory systems may function better than normal in order to adapt and compensate for the partial loss of vision. For example, is hearing more important in the everyday experience of someone with only one eye? In this dissertation I will consider the consequence of partial visual deprivation from the loss of only one eye and how it affects audiovisual processing.

Typical visual development

The visual system is not fully mature at birth and continues to develop throughout infancy until it reaches adult levels in late childhood and adolescence (see Daw, 2006 for a review). Multiple critical periods exist in postnatal visual development where a number of different visual functions are maturing along with their underlying neural substrates. During a critical period the nervous system is vulnerable to environmental stimuli where, if appropriate stimuli are not provided, the development of that function may be hindered or eliminated. There are three types of critical periods present during postnatal visual development: 1. Critical period of development: where environmental experience has an impact on a function while it is rapidly developing; 2. Critical period for disruption: where a postnatal experience has an adverse effect on the development of a function; 3. Critical period of recovery: where a disrupted function can be recovered. Critical periods for different visual functions such as acuity or motion perception can emerge at different times (Daw, 2006). For example visual acuity does not fully develop to adult sensitivity levels until the age of 4-6 years (Ellemberg et al., 1999; Mayer & Dobson, 1982), whereas mixed literature regarding the development of directional motion sensitivity reports achieving adult sensitivity levels between the age of 3 and adolescence (Ellemberg et al., 2002; Hadad et al., 2011; Parish et al., 2005).

Cortical processing of vision: The intact visual pathway consists of retinal ganglion cell axons from each eye (optic nerve) passing through the optic chiasm where approximately half of the axons continue on ipsilaterally (uncrossed fibers) and half continue on contralaterally (crossed fibres) via optic tracts (Fukuda et al., 1989; Kupfer, Chumbley & Downer, 1967). The majority of these fibres (~90%) terminate in the lateral geniculate nucleus (LGN), located in the thalamus, a subcortical structure with nuclei that process all sensory modalities except for olfaction (Perry & Cowey, 1984; Perry, Oehler & Cowey, 1984; Wallace, Wilkinson & Stein, 1996; Gottfried & Zald, 2005). The LGN is a subcortical thalamic nucleus, separated into eye-specific layers, that processes visual information. The remaining 10% of fibres project to other subcortical structures such as the superior colliculus (control of eye movements and multisensory integration), pretectum (regulating pupillary light reflexes) and hypothalamus (circadian rhythms) (Perry & Cowey, 1984; Perry, Oehler & Cowey, 1984; Wallace, Wilkinson & Stein, 1996). Feedback of information from the cortical regions that these subcortical structures project to is also received. The LGN projects to the ipsilateral primary visual cortex (V1, striate cortex), that is located in the calcarine sulcus of the occipital lobe via the optic radiations. V1 contains six layers that are functionally unique and each hemisphere processes input from the contralateral hemifield (see Howard, 2002). Both eyes innervate cells within V1; however, the majority of these cells respond predominantly to input from only one eye and are grouped into ocular dominance columns based on which eye the cell preferentially responds to (Hubel & Wiesel, 1969; Horton, Dagi, McCrane, & de Monasterio, 1990; LeVay, Hubel, & Wiesel, 1975). Information from V1 is sent to areas beyond V1, such as V2, V3, V4, V5, V6 and MT+ responsible for higher level visual processing (Ho & Giaschi, 2009; Hubel & Livingstone, 1987: McKeefry et al., 2008; Tootell et al., 1995).

Cross-sensory adaptation due to complete visual deprivation

There is a growing body of research showing that complete deprivation of the visual system from the loss of both eyes early in life results in changes in the remaining senses. If atypical visual experience occurs during the critical periods this can lead to visual deficits (Daw, 2006). Early disruption of vision, prior to the completion of the developmental critical periods will result in deficits in visual processing and this in turn may affect the development of complementary senses.

Animal models: A number of behavioural adaptations demonstrating increased reliance on non-visual senses have been observed in rats that have had both eyes surgically removed at birth. These include: increased sniffing, increased range of vibrissal movement and increased response to noise in comparison to rats with both eyes intact (Dyson et al., 1991). Newborn hamsters with both eyes surgically removed show activation in visual areas of the brain in response to auditory stimuli in addition to the activation that is regularly seen in the auditory pathway (Izraeli et al., 2002). Similarly, adult opossums with both eyes surgically removed early in life show activation in visual areas of the brain for both auditory and somatosensory stimuli (Kahn & Krubitzer, 2002). Enhanced auditory processing after complete visual deprivation from binocular eyelid suture has also been observed through intracellular recordings in cats (Rauschecker & Harris, 1983). Together, these examples build a case for the possibility of enhanced processing ability and cortical recruitment of unused visual areas in response to complete early visual deprivation. However, there is also contrary evidence for disruption of complementary senses when the visual system is compromised. Barn owls raised blind but with intact hearing, have decreased precision in their auditory space maps indicating intact vision might be essential to develop some aspects of audition (Knudsen, 1988).

Human data: Recently, humans with complete visual deprivation have also shown evidence for changes in other sensory systems that suggest enhanced abilities with their remaining senses following a complete loss of a sensory system. Congenitally blind individuals have shorter response times for auditory discrimination tasks (Röder et al., 1999), faster processing of language (Röder et al., 2002), enhanced sound localization

(Lessard et al., 1998) and enhanced tactile perception (Sathian, 2000, Goldreich & Kanics, 2003) compared to sighted individuals. This suggests underlying physiological changes within the systems responsible for these senses to support these behavioural enhancements. The visual cortex appears to be recruited or reorganized by other sensory systems in the congenitally blind. This notion is supported by recent neuroimaging studies of auditory processing (Merabet et al., 2009; Collignon et al., 2009) and sound localization (Weeks et al., 2000), as well as, tactile perception and Braille reading (Kupers et al., 2007; Sadato et al., 1996; Cohen et al., 1997; Buchel et al., 1998) and smell ability (Majchrzak et al., 2017). All of these studies show activation of the visual cortex for sensory stimuli normally processed elsewhere in the brain. Similar to evidence from animal models, there is also contrary evidence for disruption of complementary senses when the visual system is compromised in humans with congenital blindness. Congenitally blind individuals have decreased accuracy for localizing sounds in the vertical plane (Lewald, 2002), judging distance of auditory stimuli (Wanet & Veraart, 1985) and complex horizontal sound localization (Gori et al., 2014). Overall, these findings demonstrate that in cases of complete sensory deprivation, specifically blindness, it is possible for other intact sensory systems to adapt and compensate for the loss of vision. I now turn to the case of partial visual deprivation. Would this adaptive plasticity benefiting the remaining intact senses also hold true for a case of partial sensory deprivation such as the early loss of one eye?

Monocular enucleation

A unique model for examining the consequences of the loss of binocularity is unilateral enucleation, the surgical removal of one eye (see Steeves, Gonzalez & Steinbach, 2008, for a review). It is unlike other forms of monocular visual deprivation such as cataract (cloudy lens), strabismus (misalignment of eyes), ptosis (eyelid droop) or anisometropia (unequal focusing power of each eye) that leave abnormal visual input resulting in competitive binocular interactions. Removing the eye completely eliminates all forms of visual input to the brain from that eye. This results in a single stream of information to the visual system and a lack of competitive binocular interactions (Figure 1.1) (Steeves et al., 2008). Early monocular enucleation is a particularly useful model of study since the visual system has not been exposed to abnormal visual input from the removed eye.

Early monocular enucleation has been the treatment of choice for a rare group of individuals who have been diagnosed with retinoblastoma. Retinoblastoma, a malignant tumor of the retina, typically occurs before 5 years of age and accounts for approximately 6% of all childhood cancers (Broaddus, Topham & Singh, 2009a). Unilateral retinoblastoma accounts for approximately 60% of these cases where the mean age of diagnosis is 24 months (Lohmann & Gallie, 2013).

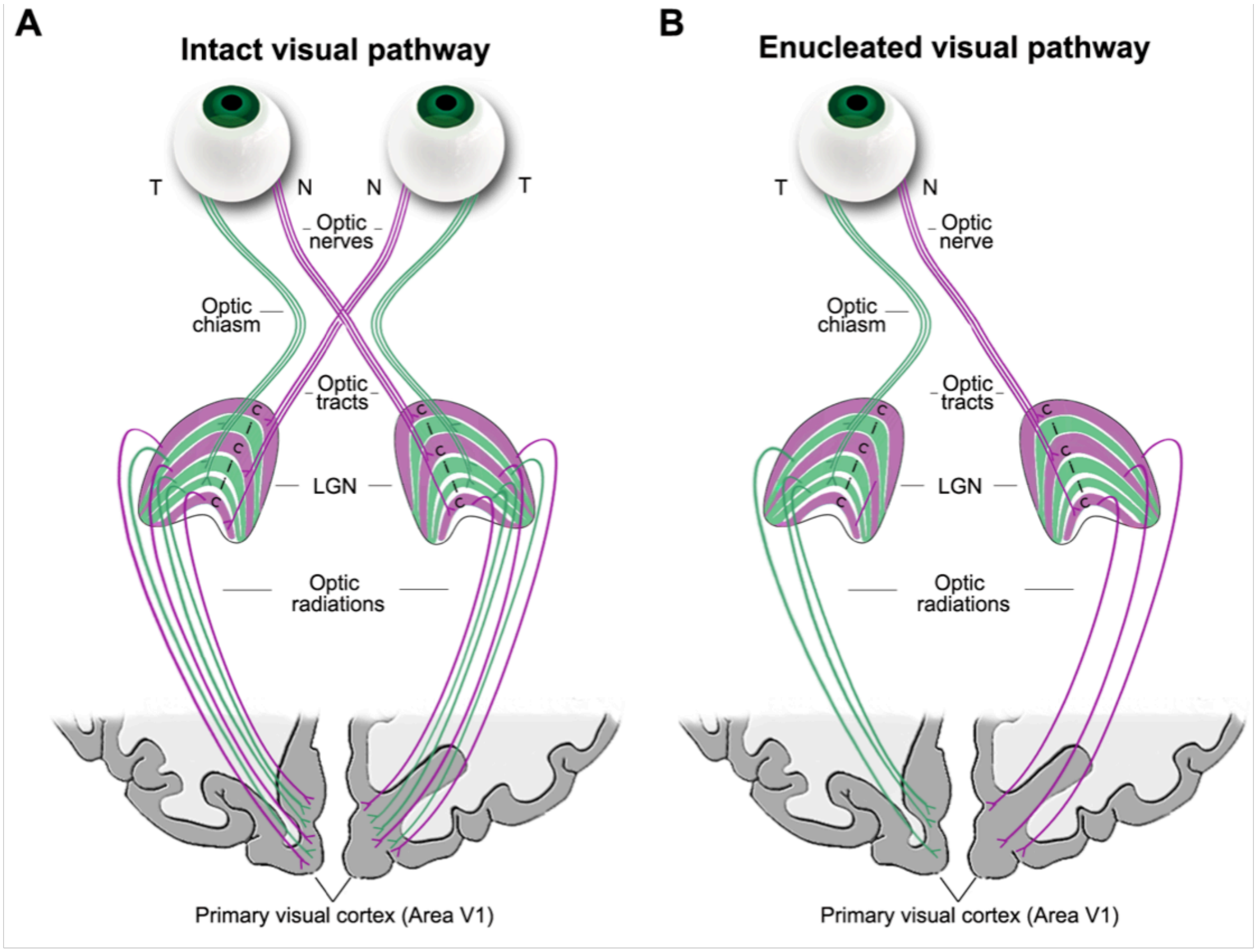

Figure 1.1. A. Schematic illustration of a binocularly intact brain. Visual information from each eye is relayed through the optic nerve by the temporal (green) and nasal (purple) retinal fibres that converge at the optic chiasm. Crossed (nasal) fibres are relayed to the contralateral LGN and the uncrossed (temporal) fibres are projected to the ipsilateral LGN. Information is then projected by optic radiations to the primary visual cortex (V1). B. Schematic illustration of a brain post enucleation that visualizes the complete deafferentation resulting from the removal of one half of the visual inputs to the brain. Figure from Kelly et al., 2014 (under the terms of the Creative Commons Attribution License (CC BY) permission is not required for this type of reuse).

Visual adaptation due to partial visual deprivation

Losing one eye early in life, during postnatal visual system maturation, has been shown to lead to both enhanced and reduced visual function. These enhancements and reductions in performance depend on whether one is measuring visual spatial ability or visual motion processing and oculomotor systems (reviewed in Steeves et al., 2008; Kelly, Moro & Steeves, 2013). A number of behavioural studies have been conducted with people who have only one eye to assess visual abilities and to investigate what types of accommodations the brain might make after losing half of its visual input (see Steeves et al., 2008; Kelly, Moro & Steeves, 2013). In an early study conducted by Freeman and Bradley (1980), people with one functional eye had normal Snellen acuity but higher Vernier acuities (ability to detect the alignment or lack of alignment of two parts of a broken line, a hyperacuity) compared to control participants viewing with one eye patched. Vernier acuity may specifically be enhanced in people who are viewing with one dominant eye since it is known to improve with practice (Poggio et al., 1992), implying that people who have one functional eye have had more practice viewing in this way compared to eye-patched controls. Heightened sensitivity for perceiving line orientation (ability to align a dot with a horizontally or obliquely oriented bar) is also observed for people with one eye compared to eye-patched controls (Reed et al., 1995). People with one eye demonstrate superior contrast sensitivity at 2, 4, and 8 cycles/degree compared to control participants viewing with their non-dominant eye patched (Nicholas, Heywood & Cowey, 1996). Furthermore, people who lost their eye before 2 years of age have better contrast sensitivity at 4 cycles/degree compared to those who lost their eye later, and moreover, compared to binocular viewing controls. These results indicate a developmental relationship between age at enucleation and contrast sensitivity, where earlier enucleation leads to larger improvement in contrast sensitivity with the remaining eye and likely facilitates cortical remapping to underlie this ability.

People with one eye also have intact and sometimes enhanced ability to perform higher-level visual tasks, such as letter recognition. Texture defined letter detection and recognition remain intact (Steeves et al., 2002) while peripheral acuity (at 7 degrees of eccentricity) is superior to eye-patched controls at lower contrasts (González et al., 2002). People with one eye have superior foveal acuity while viewing illiterate 'E' optotypes at 96%, 13.5% and 4.7% contrast (González et al., 2002). They also demonstrate better acuity when viewing Snellen-like letter charts at low and high contrasts compared to eye-patched controls and are equivalent to binocular viewing controls (Reed et al., 1996; Reed, Steeves & Steinbach, 1997).

The ability to discriminate low-contrast global shape, a more complex visual process, is also enhanced in people with one eye compared to eye-patched controls (Steeves et al., 2004). Face processing, however, has emerged as an exception. Kelly, Gallie and Steeves (2012) have recently shown that, although face processing is a unique aspect of vision, people with one eye have mild impairments in processing the shape and spacing between internal facial features. This leads to an overall deficit in processing faces holistically, where faces are processed as a whole rather than in its parts. These mild impairments are face-specific since this deficit was not replicated when viewing analogous “face like” stimuli from another visual image category, namely houses (Kelly, Gallie & Steeves, 2012).

Unlike the mainly intact observations of letter and shape perception, people with one eye have a mild impairment for motion perception (see Steeves et al., 2008 for a review). Overall, people with one eye have impaired motion-defined letter recognition compared to controls. The impairment shows a developmental relationship where poorer motion-defined letter detection is correlated with earlier loss of the eye (Steeves et al., 2002). They also overestimate the perception of time to collision of an approaching object, while controls underestimate the time to collision of an approaching object (Steeves et al., 2000). Conversely, people with one eye do not differ from controls in sensitivity to the relative motion of shearing texture, however, they do show reversed velocity discrimination biases compared to binocular viewing controls (Bowns, Kirshner & Steinbach, 1994). This reversed bias could be an attempt to compensate for the lack of binocular disparity information (a binocular cue to depth) by attempting to use motion parallax (a monocular cue to depth) to calculate depth perception. It was predicted that perhaps an "anticipatory eye movement" is made based on the participant's expectation of where the stimuli would be moving which in turn affects perceived direction discrimination. Direction discrimination of coherent horizontal motion is also not impaired in people with one eye relative to controls (Steeves et al., 2002) but instead demonstrates response asymmetries favouring nasalward over temporalward motion, similar to a small asymmetry observed with eye movement responses measured by optokinetic nystagmus (OKN; involuntary eye movement in response to a movement of the visual field across the retina) (Day, 1995; Reed et al., 1991).

In a study conducted to see whether people with one eye performed differently during a visually guided reaching task, no differences were found in the kinematics of the grasping movements (Marotta et al., 1995). People with one eye did, however, perform faster and larger lateral and vertical head movements, perhaps as a way to better utilize retinal motion cues of depth, such as motion parallax, to assist with grasping an object in front of them to accommodate for lack of stereoscopic vision (Marotta et al., 1995). Table 1.1 summarizes the differences in visual behavioural performance observed in people with one eye compared to binocular viewing controls.

Structural Changes: Few studies have investigated structural changes in people who have had one eye removed early in life. Postmortem studies describe a reduction in optic chiasm width (Horton, 1997), degeneration of optic tracts and transneuronal degeneration of deafferented geniculate cells (Goldby, 1957; Hickey & Guillery, 1979; Beatty et al., 1982) in patients who have lost one eye later in life. In addition, stronger functional activity in V1 contralateral to the remaining eye has been found in children under sedation who have had their eye removed early in life compared to age matched controls (Barb et al., 2011). Recently, significant degeneration of the anterior visual system, including decreased optic chiasm volume and width were found in people who lost one eye early in life compared to binocular controls (Kelly et al., 2014). As is expected, when 50% of the signal to the visual system is deafferented after one eye is removed, people with one eye have an overall decrease in LGN volume compared to binocular controls (Kelly et al., 2014). Surprisingly, the volume of the LGN contralateral to the remaining eye is less reduced likely from recruitment of some of the deafferented LGN cells, providing evidence that even at the subcortical level, reorganization of the visual system is possible after losing one eye early in life (Kelly et al., 2014). A subsequent study revealed that, compared to binocular viewing controls, people with one eye have increased surface area and gyrification in visual, auditory, and multisensory cortices (Kelly et al., 2015). Consistent with the subcortical findings, increased surface area in visual regions was restricted to V1 and inferior temporal cortex contralateral to the remaining eye (Kelly et al., 2015). Recently, diffusion tensor imaging (DTI) to examine white matter tracts in the visual and auditory systems has revealed altered white matter connectivity in people who have had one eye removed early in life compared to binocular viewing controls (Wong et al., 2017). Tracts were consistently greater contralateral to the removed eye in the optic radiations, V1-LGN projections and interhemispheric V1 projections of people with one eye compared to binocular viewing controls (Wong et al., 2017). These asymmetrical changes were likely a reflection of the differences observed in the LGN volume and optic tract contralateral to the removed eye previously demonstrated in this group (Kelly et al., 2014). Table 1.2 summarizes the differences in cortical and subcortical structure observed in people with one eye compared to binocular viewing controls.

Overall, when one eye is removed early in life general visual abilities remain intact despite mild impairments in face perception, motion perception, and an altered anterior visual pathway. Few studies have examined whether people who have had an eye removed early in life also show evidence for changes in other sensory systems similar to those with congenital blindness following the removal of a portion rather than the entirety of the visual system.

	Reduced	Normal	Enhanced
Vision	Motion defined letter recognition (Steeves et al., 2002)	Snellen acuity (Freeman & Bradley, 1980)	Vernier acuity (Freeman & Bradley, 1980)
	Reduced velocity discrimination biases (Bowns, Kirshner & Steinbach, 1994)	Texture defined letter detection and recognition (Steeves et al., 2002)	Line orientation perception (Reed et al., 1995)
	Face perception regarding the shape and spacing between internal facial features (Kelly et al., 2012)	Sensitivity to relative motion of shearing texture (Bowns, Kirshner & Steinbach, 1994)	Contrast sensitivity at 2, 4 and 8 cycles/degree (Nicholas, Heywood & Cowey, 1996)
		Direction discrimination of coherent horizontal motion (Steeves et al., 2002)	Peripheral acuity at 7 degrees of eccentricity (González et al., 2002)
		Visually guided reaching with the use of faster, larger head movements (Marotta et al., 2005)	Foveal acuity for illiterate 'E' optotypes at 96%, 13.5% and 4.7% contrast (González et al., 2002)
Audition			Auditory localization (within 78 degrees to the left or right of straight ahead except for the extreme periphery) (Hoover et al., 2012)
Audiovisual	Lack typical pattern of visual dominance (ie. Colavita effect) (Moro & Steeves, 2012; 2013)	Localization variance when presented with perceptually equal auditory and visual stimuli despite longer reaction times (Moro et al., 2014)	

Table 1.1. Summary of reduced, normal and enhanced behavioural differences in people with one eye compared to binocular viewing controls.

	Reduced	Normal	Enhanced
Structural	Optic chiasm volume and width (Horton, 1997; Kelly et al., 2014)		Stronger functional activity in V1 contralateral to the remaining eye in children under sedation (Barb et al., 2011)
	Degeneration of optic tracts and deafferented geniculate cells in patients with late enucleation (Goldby, 1957; Hickey & Guillery, 1979; Beatty et al., 1982)		Surface area and gyrification in visual, auditory and multisensory cortices (Kelly et al., 2015)
	LGN volume; contralateral LGN to the remaining eye is less reduced (Kelly et al., 2014)		
	Asymmetrical white matter tracts that are greater contralateral to the removed eye in the optic radiations, V1-LGN projections and interhemispheric V1 projections (Wong et al., 2017)		

Table 1.2. Summary of reduced, normal and enhanced structural differences in people with one eye compared to binocular viewing controls.

The effect of monocular enucleation on auditory processing

Do people with one eye demonstrate enhanced sound localization similar to people with early blindness (i.e. Lessard et al., 1998)? A recent study focused on whether early eye removal in humans also results in adaptation in other senses similar to the early blind human and animal models. Hoover, Harris and Steeves (2012) investigated auditory spatial localization in people who had one eye surgically removed early in life (but maintained normal or corrected to normal vision in their remaining eye) compared to control participants who were monocular viewing (with one eye patched), binocular viewing or with their eyes closed. Auditory localization was consistently more accurate in all locations (i.e., within 78 degrees to the left or right of straight ahead) except for the extreme periphery (which most studies do not measure) in people with one eye compared to control participants who were binocular viewing, eye-patched or with both eyes closed. Moreover, people with one eye also demonstrated improved monaural (one ear) sound localization and did not show the typical tendency to mislocate sounds towards the 'straight ahead' as did controls (Hoover et al., 2012). Although this enhancement was found across the majority of the frontal visual field, it is important to note that people with one eye exhibited much larger errors compared to controls when locating sounds in the extreme periphery. It was speculated that the errors in the extreme periphery may be due to calibration errors associated with the loss of binocular depth perception and their interaction with binaural sound localization cues. These results provide the first evidence that individuals with one eye have improved sound localization compared to controls.

Audiovisual processing

Interactions between vision and hearing are not uncommon and are usually associated with our perception of events in the world. Integrating vision and hearing is an important aspect of how we process our rich sensory environment. Audiovisual integration is required and engaged whenever anything that makes a sound is observed (for example, a person speaking or a roaring motorcycle). Humans can take advantage of a variety of redundant information from different sensory systems, including vision and audition, which contribute to facilitating the processing of each other that help to make our perceptions of the world extremely accurate. What these cues are and how important each cue is in particular tasks has been studied extensively (Alais et al., 2010; Welch & Warren, 1980; Bertelson & Aschersleben, 1998; Battaglia et al., 2003). Studying relatively rare patient cases (such as people with one eye), who have a sensory deficit that interferes with typical perception, helps to determine the importance of each unimodal cue and how integrated percepts are created (Welch & Warren, 1980; Bertelson & Aschersleben, 1998).

Perceptual illusions created by producing a deliberate discrepancy between the senses, often causes the brain to bias the processing of one sensory modality over the other, known as intersensory bias (Welch & Warren, 1980). This is the brain's attempt to "maintain normal perception" by making a "best guess" of what is going on (Welch & Warren, 1980). According to the "assumption of unity," the greater the magnitude of intersensory bias, the more likely a participant will perceive two stimuli from different senses (such as audition and vision) as a single event (Welch & Warren, 1980). The strength of the assumption of unity is based on several factors such as shape, size and motion of the stimuli, as well as, the relative weighting assigned by the observer to these factors (Welch & Warren, 1980). For example, this means that according to the assumption of unity, if two stimuli are at the same location and are relatively the same in shape they would be more likely to be perceived as if they were one stimulus rather than two.

The integration of multiple unisensory events into a single percept, called multisensory integration, can result in intersensory facilitation. That is, faster processing of multisensory, compared to unisensory, stimuli (Sinnett et al., 2008). Here, information received from multiple senses is combined when both the auditory and visual components of the audiovisual stimulus occur at perceptually the same time from perceptually the same space in accordance with the assumption of unity (Alais et al., 2004). Conversely, another result of multisensory integration could be intersensory competition. Where, according to the assumption of unity, a perceptual bias can occur as a result of the dominance of one sensory modality over another (Sinnett et al., 2008). An example of such sensory bias is the ventriloquism effect. When the perceptual system is presented with an audiovisual stimulus, where the auditory portion of the stimulus is displaced spatially relative to the visual portion of the stimulus, the result is the perception of an event at a single location in the vicinity of the visual stimulus. This perceived location of sound towards the visual stimulus indicates the presence of a strong visual bias over audition (Welch & Warren, 1980). This illusory percept has been called the 'ventriloquism effect', since it is similar to the way in which the voice of a ventriloquist performer seems to be projected out of a puppet's mouth during a ventriloquism performance (Alais et al., 2010; Welch & Warren, 1980; Bertelson & Aschersleben, 1998).

The effect of monocular enucleation on audiovisual processing

Binocularly intact individuals have the consistent tendency to preferentially process visual over auditory information for audiovisual (bimodal) events (Colavita, 1974; Egeth & Sager, 1977; Colavita & Weisberg, 1979; Sinnett et al., 2008; Spence, 2009; Spence, Parise & Chen, 2011). This is known as the Colavita visual dominance effect (Colavita, 1974). People with one eye do not show the typical pattern of visual dominance when asked to categorize rapidly presented audiovisual targets, but rather, they show equivalent auditory and visual processing suggesting an enhanced weighting is applied to the auditory component of a bimodal stimulus (Moro & Steeves, 2012). These results persisted even when the temporal load was increased in the same task by asking participants to detect and discriminate when they were presented with an audio, visual, or bimodal repetition of two of the same back-to-back stimuli (Moro & Steeves, 2013). Although the Colavita effect is not a measure of multisensory integration, the decrease in visual dominance may leave open the possibility for adaptation of other senses, such as hearing, similar to the examples set out by animal and early blind models.

When presented with paired auditory and visual stimuli that are spatially displaced relative to one another, a ventriloquism effect study, people with one eye show no difference in variance of audiovisual localization compared to control groups viewing binocularly or with one eye-patched when presented with perceptually equal auditory and visual stimuli (Moro et al., 2014). However, unlike binocular and eye-patched controls, people with one eye take longer to localize unimodal visual stimuli compared to unimodal auditory stimuli (Moro et al., 2014). Moreover, their visual response latencies are significantly slower than those of either the binocular or eye-patched control groups (Moro et al., 2014). Nonetheless, like both control groups, people with one eye perform audiovisual localization optimally in accordance with the Maximum Likelihood Estimation model (Moro et al., 2014). It is possible that plasticity during postnatal development alters their ability to process sensory information and results in slower visual processing time in order to achieve normal audiovisual integration performance. 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 the present time. It is possible that changes in visual neural connectivity and morphology lead to slower visual processing time. Despite these changes to the visual system, slower processing time appears to not affect accuracy of visual behaviour.

Overall, there is evidence of the presence of adaptive perceptual accommodations in people who have lost one eye early in life that may serve to mitigate the loss of binocularity during early brain development. These adaptive perceptual accommodations may allow people with one eye to demonstrate altered sensory processing compared to binocularly viewing individuals, likely as an adaptive consequence to the 50% reduction in visual input to the brain. Presumably, these adaptations occur as a result of cortical/subcortical remapping which allows the brain to modify itself after it has been compromised, promoting learning, remembering and recovery from injuries (Guzzetta et al., 2010).

There are a variety of tasks that can be used as a tool to investigate audiovisual interactions, from measuring the physical limits of multisensory integration based on the assumption of unity or exploiting these assumptions resulting in audiovisual illusions. The following tasks examining the temporal binding window, double flash illusion, dynamic visual capture, McGurk effect and person/object identification have been employed throughout my dissertation to measure specific aspects of audiovisual processing in a patient group who has partial visual deprivation due to the removal of one eye early in life. Specific hypothesis regarding each task will be developed in a dedicated section to follow.

Temporal binding window

Within the temporal domain, there are differences in propagation speeds of visual and auditory information throughout space, as well as, sensory transduction and processing time (Sugita & Suzuki, 2003; Powers, Hevey & Wallace, 2012). It has been well established that light travels much faster through air compared to sound (300 000 000 m/sec vs. 330 m/sec) however, sensory processing is slower for vision compared to sound (50 ms vs. 10 ms) (Vroomen & Keetles, 2010). A "temporal window" exists where, even if offset by a short amount of time, auditory and visual stimuli will still be integrated together (see Vroomen & Keetels, 2010 for a review). Typically, this temporal binding window (TBW) is approximately 200ms in duration and has a number of characteristic features including an asymmetry in window width that is wider when the auditory stimulus is presented before the visual stimulus (Stevenson, Zemtsov & Wallace, 2012; Vroomen & Keetels, 2010). This asymmetry indicates that the point of subjective simultaneity is perceived when the visual stimulus precedes the auditory stimulus (Vroomen & Keetles, 2010). The window has also been shown to increase in width based on the complexity of the stimulus. For example, face and voice stimuli produce a larger window compared to other non-voice stimuli including simple flashes and beeps (Navarra et al., 2005; Stevenson & Wallace, 2013). Additionally, individual differences can contribute to altered temporal binding, specifically within some clinical populations. Larger TBWs have been observed in individuals with dyslexia and autism spectrum disorder (ASD; Foss-Feig et al., 2010; Kwakye et al., 2011; Taylor, Isaac & Milne, 2010; Hairston et al., 2005) often resulting in the erroneous integration of auditory and visual events that do not come from the same source. Measuring the temporal binding window will allow me to estimate the physical limit of temporal integration of low-level auditory and visual stimuli in people with one eye and compare it with control groups.

Double flash illusion

Sensory experience typically relies on the integration of various unimodal sensory events. When unisensory events are not congruent they can result in perceptual errors that are dependent on the stimulus conditions and task such as stimulus brightness/ loudness, presentation duration and whether the task investigates detection or discrimination (Abadi & Murphy, 2014). When auditory and visual stimuli are incongruent in their temporal presentation the resulting perception can be illusory in nature. For example, when a single flash of light is paired with multiple tones it typically gives the illusion that multiple light flashes occurred based on the number of tones present. This is known as the double flash illusion (also referred to as the sound induced flash illusion) (Shams et al., 2000). The double flash illusion is a compelling example of how the presentation of a stimulus in one sensory modality can influence the perception of a stimulus in another sensory modality (Stevenson, Zemtsov & Wallace, 2012). The over estimation of flashes perceived in the double flash illusion is known as a sound induced fission illusion (Shams et al., 2000; Anderson et al., 2004; Abadi & Murphy, 2014). The underestimation of flashes perceived in tasks where more than one flash is incongruently paired with a tone is known as a sound induced fusion illusion (Shams et al., 2000; Anderson et al., 2004; Abadi & Murphy, 2014). The fission and fusion illusions have been shown to be associated with auditory capture, or "auditory driving," where perception of a visual stimulus is affected by irrelevant auditory stimuli (Abadi & Murphy, 2014). Susceptibility to this illusion is also directly related to the width of the TBW where a greater number of flashes will be perceived by individuals who have a wider TBW. Measuring the double flash illusion will allow me to investigate whether people with one eye are susceptible to the illusory auditory capture of vision. Furthermore, it will allow me to investigate whether people with one eye, who may have a rebalancing of visual processing due to the reduction of visual input to the brain, demonstrate a relationship between temporal integration of audiovisual stimuli and susceptibility to the double flash illusion.

Dynamic visual capture

The investigation of the integration of audiovisual moving signals is important given that many signals throughout the external world are dynamic and often are crucial for survival (Harrison, 2012; see Soto-Faraco et al., 2003 for review). The depth plane is particularly important since the rapid detection of looming motion can signal the approach of a potentially threatening object and the accurate detection of receding motion can signal its retreat (Harrison, 2012). Both the visual and auditory modalities can provide reliable information about looming and receding motion (Harrison, 2012). It has been shown that the adaptation of motion in one modality can influence the perceived direction of motion in a second modality (Jain et al., 2008; Kitagawa & Ichihara, 2002). Dynamic visual capture is a phenomenon where a moving visual stimulus influences the perception of a moving auditory stimulus. Dynamic visual capture is strongly related to the double flash illusion where instead of an auditory stimulus driving the perception of a visual stimulus, it is an example of a visual stimulus driving of an auditory stimulus. In the depth plane, dynamic visual capture has been shown for both stationary auditory stimuli that are perceived as moving in the direction of the visual stimulus (Mateef et al., 1985) and dynamic auditory stimuli that are perceived moving in the direction of the visual stimulus, even if they are actually moving in the opposite direction (Jain et al., 2008; Kitajima & Yamashita, 1999). Measuring dynamic visual capture in depth will allow me to explore whether people with one eye are susceptible to visual capture of audition using low-level auditory and visual stimuli despite having a reduction of visual input to the brain and known deficits in binocular depth perception.

McGurk effect

The accurate perception of speech is highly influenced by audiovisual integration. Auditory speech information is greatly enhanced by the presence of visual lip movements, especially under noisy conditions (Szycik et al., 2012). The McGurk effect is an audiovisual illusion where a new syllable is perceived when visual lip movements do not match the corresponding auditory sound (McGurk & MacDonald, 1976). The McGurk illusion has become a popular tool for studying the mechanisms underlying multisensory integration, despite having substantial inter-subject variability (Alsius, Paré & Munhall, 2017; Beauchamp, Nath & Pasalar, 2010). In a recent review paper, Alsius and colleagues (2017) suggest three factors that might contribute to individual differences in the perception of the illusion: 1. Superior sensitivity to detecting audiovisual correspondences, where the auditory and visual sensory signals would not erroneously be attributed as belonging to the same event; 2. Higher/lower weighting of the visual or auditory cues, where the higher weighted modality will more greatly contribute to the perception of the event; 3. An inefficient combination of the two cues, where poorer integration will contribute to the perception of individual auditory and visual events that are not fused into a single event (Alsius, Paré & Munhall, 2017). Neural substrates have also been implicated in accounting for individual differences in the perception of the McGurk effect. The application of transcranial magnetic stimulation (TMS) to the left superior temporal sulcus (STS) reduced the perception of the McGurk effect in individuals who typically perceive it (Beauchamp, Nath & Pasalar, 2010). Further, fMRI shows greater activation of the left STS was correlated with greater perception of the McGurk effect (Nath & Beauchamp, 2012). Clinical populations have also been shown to demonstrate a difference in their perception of the McGurk effect. People with amblyopia have a reduced McGurk effect that even persists with both binocular and fellow eye viewing (Narinesingh et al., 2014). This indicates that the underlying causes are associated with more complex sensory processes that are not specific to visual acuity (Narinesingh et al., 2014) but are likely to be higher level and cortical in nature. Measuring the McGurk effect will allow me to determine whether people with one eye perceive higher-level audiovisual illusory stimuli the same as controls. It is possible that a dissociation will emerge between performance in experiments that use low-level versus high-level audiovisual stimuli.

Person and object identification

Face perception is a unique and multi-faceted aspect of vision (Leopold & Rhodes, 2010). Typical face processing relies on the ability to perceive a face as a 'whole' rather than the sum of its individual features, known as holistic face processing (see Rivolta, 2014 for a review). There are dedicated neural substrates that have been shown to preferentially process faces such as the Fusiform Face Area (FFA, Kanwisher et al., 1997), occipital face area (OFA, Gauthier et al., 2000), superior temporal sulcus (STS) and the anterior temporal face patch (ATFP) (Gobbini & Haxby, 2007; Haxby et al., 2000; Kreigeskorte et al., 2007). These areas are necessary for holistic face processing, face identification recognition, facial feature processing and facial expression processing (Rivolta, 2014).

The ability to identify a person is facilitated when face information is integrated with voice information through crosstalk between the unimodal visual and unimodal auditory percepts (Campanella & Belin, 2008). Previous exposure to combined face-voice information during person identity encoding facilitates identification of that individual when only unimodal cues (face or voice) are available (Ellis, Jones & Mosdell, 1997; Schweinberger, Herholz & Sommer, 1997; Sheffert & Olson, 2004; von Kriegstein et al., 2008). Bimodal identity recognition shows interference effects (increased reaction time and decreased accuracy) when identifying bimodal (face-voice) stimuli (Joassin et al., 2004). This is because visual face recognition is superior to voice recognition. The addition of voice information interferes with the efficient processing of the face (during bimodal face-voice pairings). When face stimuli are degraded and therefore less reliable compared to voice stimuli, bimodal stimulus presentations lead to an enhancement effect (Joassin, Maurage & Campanella, 2008). These results indicate that the more reliable sensory information, which is audition in the case of degraded face stimuli, has a greater influence on person identity recognition (Joassin, Maurage & Campanella, 2008). Face-voice integration effects, similar to those found in healthy controls (Campanella & Belin, 2008), are seen in infants as young as 4 months of age (Bahrick, Netto & Hernandez-Reif, 1998) and in non-human primates (Izumi & Kojima, 2004). This suggests that face-voice identification improves with development and experience as older infants (7 months of age) have better face-voice matching compared to younger infants (4 months of age) (Bahrick, Netto & Hernandez-Reif, 1998). Measuring person identity in people with one eye will allow me to determine whether they have a rebalancing of high-level, socially complex auditory or visual information, given their reduction of visual input to the brain that affects their ability to correctly identify people.

Overall, the temporal binding window, double flash illusion, dynamic visual capture of audition, McGurk effect and person identity recognition provide ways in which audiovisual processing can be examined in people who have lost an eye early in life. These tasks have been designed to explore audiovisual integration from basic low-level temporal integration to high-level, ecologically relevant person identification. These tasks will contribute to a growing body of research quantifying the behavioural effects of partial visual deprivation and will provide the framework for investigations to observe reorganization at the cortical level.

Medial geniculate body

The medial geniculate body (MGB) of the thalamus plays a central role in auditory processing (Devlin, 2006; Bartlett, 2013). It relays auditory information for higher order processing in the primary auditory cortex, however, substantial reciprocal connections from the primary auditory cortex back to the MGB also exist (Bartlett, 2013; Lee et al., 2004; Lee, 2012; Pandya, Rosene & Doolittle, 1994) as they do between the visual cortex and the visual thalamus (De Courten & Garey, 1982). This combination of ascending/descending sensory connections allows for the perception of sounds (Bartlett, 2013). In humans, functional magnetic resonance imaging (fMRI) has shown activation in the MGB during sound localization and sound recognition (Maeder et al., 2001), as well as, speech and emotional voice discrimination (von Kriegstein et al., 2008; Ethofer et al., 2012). Cortical feedback can alter MGB responses and provide dynamic gain enhancement or suppression through direct excitatory (corticothalamic feedback) or indirect inhibitory (corticothalamic influence on the thalamic reticular nucleus (TRN)) signals (Zhang et al., 1997; Bartlett, 2013). This gain control may contribute to enhancing auditory attention and context memory, important for predicting words in a spoken sentence (Bartlett, 2013).

In addition, non-auditory stimuli also activate the MGB. Animal studies in rats have shown that the MGB responds to light flashes or rewards, indicating that it plays a role in integrating multisensory stimuli and may provide an enhanced contextual response (Komura et al., 2001; 2005; Bartlett, 2013). Congenitally deaf mice show reorganization at the level of the thalamus through the activation of the MGB for visual stimuli (Hunt, et al., 2005). Together, these findings indicate that it is possible for primary sensory afferents, such as retinal projections, to rewire and claim unused subcortical structures, resulting in anatomical re-modeling (Hunt et al., 2005; Karlen, 2006). Reorganization of the MGB following sensory loss, however, has not been studied extensively in humans. Given the existing auditory and audiovisual behavioural differences and the morphological changes in the LGN in people with one eye, do structural changes in the MGB also exist in people who have lost one eye early in life?

General purpose and hypothesis

The aim of my dissertation is to further expand our understanding of the effects of losing one eye early in life on the development of audiovisual processing both behaviourally and in terms of underlying neural structural representation. Would such an individual also adapt the processing of audiovisual sensory information in order to compensate for the partial loss of vision? Would any adaptation that might occur across other senses possibly be as a result of subcortical or cortical remapping? I will conduct seven experiments, divided into five experimental chapters, that focus on examining behaviour and structural correlates of audiovisual perception.

Chapter II: My previous behavioural data suggest that people with one eye might adaptively compensate during multisensory tasks. Experiment 1 further investigates the behavioural performance in people with one eye during audiovisual tasks. I conducted two separate studies that examined the temporal qualities of audiovisual integration using low-level audiovisual stimuli.

Experiment 1a: Auditory and visual stimuli are typically integrated as one bimodal stimulus if they are presented from the same spatial location at the same time. A "temporal window" exists where, even if offset by a short amount of time, auditory and visual stimuli will nonetheless be integrated together. Experiment 1a measures the temporal binding window (TBW) in people with one eye compared to binocular and patched viewing controls. I hypothesize that people with one eye will have a more precise (narrower) TBW since it has previously been shown that they have more accurate sound localization (Hoover et al. 2012) and are not visually dominant (Moro & Steeves, 2012).

Experiment 1b: When a single flash of light is paired with multiple tones it typically gives the illusion of multiple light flashes based on the number of tones present. This is known as the double flash illusion (Shams et al., 2000). Experiment 1b investigates whether people who have lost one eye are susceptible to the double flash illusion using low-level auditory and visual stimuli. I hypothesize that the susceptibility of the double flash illusion will decrease for people with one eye if they have a narrower TBW.

Chapter III: A moving visual stimulus has been shown to influence the perceived direction of a moving auditory stimulus (Harrison, 2012). Experiment 2 investigates whether people who have lost one eye demonstrate the same susceptibility to audiovisual dynamic visual capture, using low-level auditory and visual stimuli, in the depth plane as binocular and patched viewing control participants. I hypothesize that people with one eye will not demonstrate the same susceptibility to dynamic visual capture compared to controls given the mild impairments to motion processing, specifically the overestimation of time to collision (Steeves et al., 2000) and lack of visual dominance (Moro & Steeves, 2012; 2013) found in this group.

Chapter IV: Integrating visual and auditory information is essential to understand speech. In order to do this, the mouth of a speaker moving in a specific formation combined with auditory information from the voice of the speaker is integrated into a single percept (McGurk & MacDonald, 1976). The McGurk effect is an audiovisual illusion where a new syllable is perceived when visual lip movements do not match the auditory sound clip. Experiment 3 investigates whether people who have lost one eye are susceptible to the McGurk effect. I hypothesize that there will be a decreased or absent McGurk effect in participants with one eye given the previous research in other partial visual deprivation patient groups and their lack of visual dominance (Narinesingh et al., 2014; Moro & Steeves, 2012). It is possible that the McGurk stimuli will not produce a conflict since people with one eye are not visually dominant and instead only the auditory stimulus will be perceived.

Chapter V: Person identity recognition relies on the interaction of face and voice information through crosstalk between unimodal visual (face) and auditory (voice) percepts (Hoover, Démonet & Steeves, 2010). Experiment 4 investigates how people with one eye use high-level auditory and visual information for person and object identity recognition compared to binocular and eye-patched viewing controls.

Experiment 4a: Person recognition for faces, voices and face-voice pair combinations is quantified in people with one eye and compared to binocular and eye-patched controls. I hypothesize that people with one eye will demonstrate a deficit in person identification driven by a decrease in unimodal sensitivity to faces reflecting previous results indicating mild face perception impairment (Kelly, Gallie & Steeves, 2012).

Experiment 4b: Object recognition for cars, car horns and car-horn pair combinations is quantified in people with one eye and compared to binocular and eye-patched controls. I also compare across experiments to identify whether person recognition is unique compared to object recognition. I hypothesize that people with one eye will not have a deficit in object identification. Previous studies investigating higher-level aspects of spatial form vision has resulted in enhanced low-contrast global shape discrimination compared to patched viewing controls (Steeves et al., 2004) and no difference in reaction time and accuracy for discrimination of "face like" stimuli such as houses (Kelly, Gallie & Steeves, 2012). Furthermore, I hypothesize that results will differ in people with one eye for person identification compared to controls but not for object identification when comparing across tasks.

<u>Chapter VI:</u> The structure of the auditory system has not been extensively studied in people with one eye. People with one eye have been shown to exhibit increases in surface area and gyrification in both auditory (supramarginal) and multisensory (superior

temporal, inferior parietal, superior parietal) cortices compared to binocular viewing controls (Kelly et al., 2015). Experiment 5 examines the size of the medial geniculate body (MGB), a subcortical brain structure that provides the main input to the auditory cortex in people with one eye and compares them to those of binocularly intact controls. Data from this experiment will provide a better understanding of the neural correlates underlying the behavioural changes that have been previously observed in this population. I hypothesize that our patient group will display morphological changes in the form of increased MGB volume bilaterally, which will reflect the auditory behavioural changes that have been observed to date.

Together, my behavioural data in conjunction with these structural neuroimaging data will enable further exploration of the auditory, visual and audiovisual processing mechanisms in this rare patient group. This information can lead us to better understand sensory plasticity, in addition to the sensory deficits experienced by people with one eye, facilitating prediction of the outcome from the early loss of one eye on multisensory perception. This will allow us to use this group as a model to learn how to accommodate and maintain the health of less extreme forms of visual deprivation such as cataract and strabismus, as well as, to promote overall long-term visual health.

CHAPTER II

NORMAL TEMPORAL BINDING WINDOW BUT NO DOUBLE FLASH ILLUSION IN PEOPLE WITH ONE EYE[1]

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[1] Moro, S. S. & Steeves, J. K. E. (in press). *Experimental Brain Research.*

Abstract

Integrating vision and hearing is an important way in which we process our rich sensory environment. Partial deprivation of the visual system from the loss of one eye early in life results in adaptive changes in the remaining senses (e.g. Hoover, Harris & Steeves, 2012). The current study investigates whether losing one eye early in life impacts the temporal window in which audiovisual events are integrated and whether there is vulnerability to the double flash illusion. In Experiment 1, we measured the temporal binding window with a simultaneity judgement task where low level auditory and visual stimuli were presented at different stimulus onset asynchronies. People with one eye did not differ in the width of their temporal binding window but they took longer to make judgements compared to binocular viewing controls. In Experiment 2, we measured how many light flashes were perceived when a single flash was paired with multiple auditory beeps in close succession (double flash illusion). Unlike controls, who perceived multiple light flashes with two, three or four beeps, people with one eye were not susceptible to the double flash illusion. In addition, they took no longer to respond compared to both binocular and monocular (eye-patched) viewing controls. Taken together, these results suggest that the lack of susceptibility to the double flash illusion in people with one eye cannot be accounted for by the width of the temporal binding window. These results provide evidence for adaptations in audiovisual integration due to the reduction of visual input from the loss of one eye early in life.

There is a growing body of research demonstrating that complete deprivation of the visual system from the loss of both eyes early in life results in changes in the remaining senses. Since the visual system is not fully mature at birth and continues to develop throughout infancy, childhood and adolescence (see Daw, 2006 for a review) it is vulnerable to changes in sensory input during this time. If atypical visual experience occurs during developmental critical periods it can lead to visual deficits (Daw, 2006). Early disruption of vision will result in alterations in visual processing that may affect the development of complementary senses such as audition (Elbert et al., 2002, King, 2009, for a review).

Monocular enucleation, the surgical removal of one eye, is a unique model for examining the consequences of the loss of binocularity (see Steeves, Gonzalez & Steinbach, 2008, for a review). Unlike other forms of monocular visual deprivation such as cataract, strabismus, ptosis or anisometropia that leave abnormal visual input from the affected eye to the visual system, surgical removal of the eye completely eliminates all visual input to the brain from that eye (Steeves et al., 2008). Similar to the congenitally blind (Lessard et al., 1998), people with one eye have better auditory localization compared to control participants who were monocular viewing (with one eye patched), binocular viewing or with both eyes closed (Hoover, Harris & Steeves, 2012).

In order to make our perception of the world as accurate as possible, humans can take advantage of a variety of complementary, often redundant, information from different sensory systems. What these cues are and how important each is for particular tasks has been studied extensively (Alais et al., 2010; Welch & Warren, 1980; Bertelson & Aschersleben, 1998; Battaglia et al., 2003). We readily use audition and vision to understand the world. Sometimes, however, one sense can dominate over another. For example, people are typically visually dominant when asked to categorize rapidly presented, perceptually higher-level audiovisual targets consisting of line drawings and common sounds, known as the Colavita visual dominance effect (Colavita, 1974; Egeth & Sager, 1977; Colavita & Weisberg, 1979; Sinnett et al., 2008; Spence, 2009; Spence, Parise & Chen, 2011). People with one eye do not show the same pattern of visual dominance commonly observed in binocularly intact individuals in this task, instead they process auditory and visual information equally (Moro & Steeves, 2012). Even when task difficulty is increased these results persist (Moro & Steeves, 2013). This suggests that people with one eye have a preferential adaptation of the auditory component of a bimodal stimulus that contributes to balancing the way in which the two senses are processed (Moro & Steeves, 2012).

Perceptual illusions can be created by producing a deliberate discrepancy between the senses that the brain attempts to process by making a “best guess” as to what is going on in the sensory world. This often leads to a bias in the processing of one sensory modality over another in an attempt to “maintain normal perception” (Welch & Warren, 1980). According to the unity assumption, two stimuli that are at the same location and at the same time are more likely to be perceived as if they were one stimuli rather than two (Welch & Warren, 1980; see Chen & Spence, 2017, for a review). A common example illustrating this is observed while watching television, where a person perceives the sound as coming from the actor on the screen rather than the speakers on either side of the screen. This is a form of the ventriloquism effect, where the perception of a single event is displaced towards the visual (more perceptually dominant) stimulus when the components of an audiovisual stimulus are displaced relative to one another in space (Welch & Warren, 1980; Bertelson & Aschersleben, 1998; Alais et al., 2010; Alais & Burr, 2004). People with one eye show no difference in variance of audiovisual localization compared to control groups viewing binocularly or monocularly when presented with low level audiovisual flash and beep stimuli that were perceptually equated and displaced in space (Moro et al., 2014). However, they take longer to localize unimodal visual compared to unimodal auditory stimuli unlike binocular or monocular viewing controls (Moro et al., 2014). This indicates that people with one eye appear to have advantageously altered their ability to process sensory information, likely as an adaptation for their loss of visual input.

Similarly in the temporal domain, there are differences in propagation speeds of visual and auditory information throughout space, as well as, sensory transduction and processing time (Powers, Hevey & Wallace, 2012). A "temporal window" exists where, even if offset by a short amount of time, auditory and visual stimuli will nevertheless be integrated together (see Vroomen & Keetels, 2010 for a review). Typically, this temporal binding window (TBW) is approximately 200ms in duration and has a number of characteristic features including an asymmetry in window width that is wider when the auditory stimulus is presented before the visual stimulus (Stevenson, Zemtsov & Wallace, 2012; Vroomen & Keetels, 2010). The window has also been shown to increase in width based on the complexity of the stimulus. For example, face and voice stimuli produce a larger window compared to simple flashes and beeps (Navarra et al., 2005). In other words, the time over which a face and voice will be integrated into a single event source is longer compared to less complex stimuli such as light flashes and beeps.

When a single flash of light is paired with multiple tones it typically gives the illusion that multiple light flashes occurred based on the number of tones present. This is known as the double flash illusion (also referred to as the sound induced flash illusion) (Shams et al., 2000). The double flash illusion is a compelling example of how the presentation of a stimulus in one sensory modality can influence the perception of a stimulus in another sensory modality (Stevenson, Zemtsov & Wallace, 2012). Susceptibility to this illusion is directly related to the width of the TBW where a greater number of flashes will be perceived with a wider TBW (Stevenson, Zemtsov & Wallace, 2012).

In the current study, Experiment 1 measures the TBW for auditory and visual stimuli in people with one eye compared to binocular and monocular (eye-patched) viewing controls. Experiment 2 measures whether people who have lost one eye early in life are susceptible to the double flash illusion. Despite finding differences in people with one eye in audiovisual tasks (for example, lack of visual dominance (Moro & Steeves, 2012; 2013) and better sound localization (Hoover, Harris & Steeves, 2012)) we found no difference when comparing low-level audiovisual integration (Moro, Harris & Steeves, 2014). Since previous research on controls comparing across these studies (Stevenson, Zemtsov & Wallace, 2012) indicate that the double flash illusion is correlated with the width of the temporal binding window and we have no evidence for altered audiovisual integration using similar stimuli in this group, we predict that the susceptibility to the double flash illusion will reflect the size of the temporal binding window. We predict that people with one eye will show the same pattern as controls where a larger TBW will result in a higher susceptibility to the double flash illusion. This study will provide a better understanding of how people who have undergone a 50% reduction in visual input early in life process auditory and visual information and whether temporal coincidence affects multisensory integration.

Materials and Methods

Participants

People with One Eye (Monocular Enucleation, ME):

Eight adult participants who had undergone monocular enucleation (ME) at The Hospital For Sick Children participated in this study (mean age = 34 years, SD = 13). All ME participants had been unilaterally eye enucleated (6 right eye removed) due to retinoblastoma, a rare childhood cancer of the retina. Age at enucleation ranged from 4 to 66 months (mean age at enucleation = 24 months, SD = 19).

Binocular Viewing Control Participants (BV):

Twenty binocularly intact controls with a mean age of 27 years (SD = 9) were tested viewing stimuli binocularly.

Monocular Viewing (Eye-patched) Control Participants (MV):

Twenty binocularly intact participants, with a mean age of 27 years (SD = 10), completed the experiments with one eye patched. Participants' non-preferred eye was patched with a semi-opaque eye covering and translucent tape (10 right-eye covered).

All participants (ME, BV, MV) reported normal hearing and normal or corrected-to-normal acuity as assessed by an EDTRS eye chart (Precision Vision™, La Salle, IL) and wore optical correction if needed. All participants gave informed consent prior to their inclusion in the study, which was approved by the York University Office of Research Ethics and adhered to the tenets of the Declaration of Helsinki.

Experiment 1: Temporal binding window stimuli

Visual stimuli consisted of an 8° of visual angle white ring on a black background with a visual fixation cross in the centre. Visual stimuli were presented for a duration of 17 ms. Auditory stimuli consisted of a 3500 Hz pure tone with a duration of 13 ms. Stimuli were presented using VPixx Stimulus Presentation Software (VPixx Technologies Inc., www.vpixx.com). Auditory and visual stimuli were presented at 10 different stimulus onset asynchronies (SOAs: 0, 10, 20, 50, 80, 100, 150, 200, 250, 300 ms). SOAs presented were approximate based on the 60Hz refresh rate of the computer screen. Each of the 10 different SOAs was presented with visual-preceding-auditory (VA) and auditory-preceding-visual (AV) presentations (for a total of 19 different SOAs). There were 20 repetitions per SOA for a total of 380 trials presented in a random order. A 1000 ms interstimulus interval (ISI) consisting of silence and a blank screen occurred between trials (Figure 2.1).

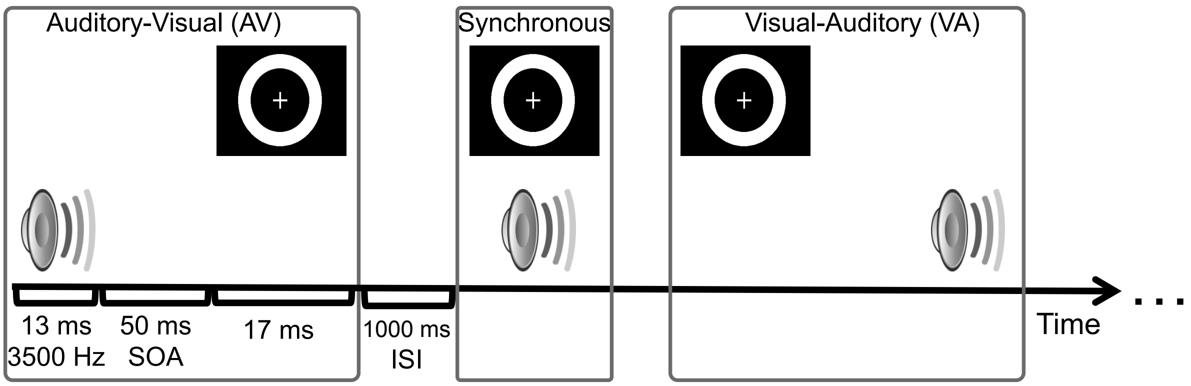

Figure 2.1. A schematic illustration of the stimuli used in the SOA task. Auditory and visual stimuli were presented at 10 different SOAs: 0 (synchronous) and 10, 20, 50, 80, 100, 150, 200, 250, 300 ms for both visual-preceding-auditory (VA) and auditory-preceding-visual (AV) conditions.

Experiment 2: Double flash illusion stimuli

Visual and auditory stimuli were identical to those used in Experiment 1. Stimuli were presented using VPixx stimulus presentation software (VPixx Technologies Inc., www.vpixx.com). Each single-flash presentation of a visual stimulus was paired with 0, 1, 2, 3, or 4 auditory stimuli. Control conditions consisted of 2, 3, or 4 presentations of a visual stimulus paired with 0 or 1 auditory stimulus. The onset of the first auditory stimulus was presented in conjunction with the onset of the first visual stimulus for all audiovisual trials. There were 20 repetitions of each audiovisual combination for a total of 220 trials presented in a random order. A 1000 ms ISI consisting of silence and a blank screen occurred between each trial (Figure 2.2).

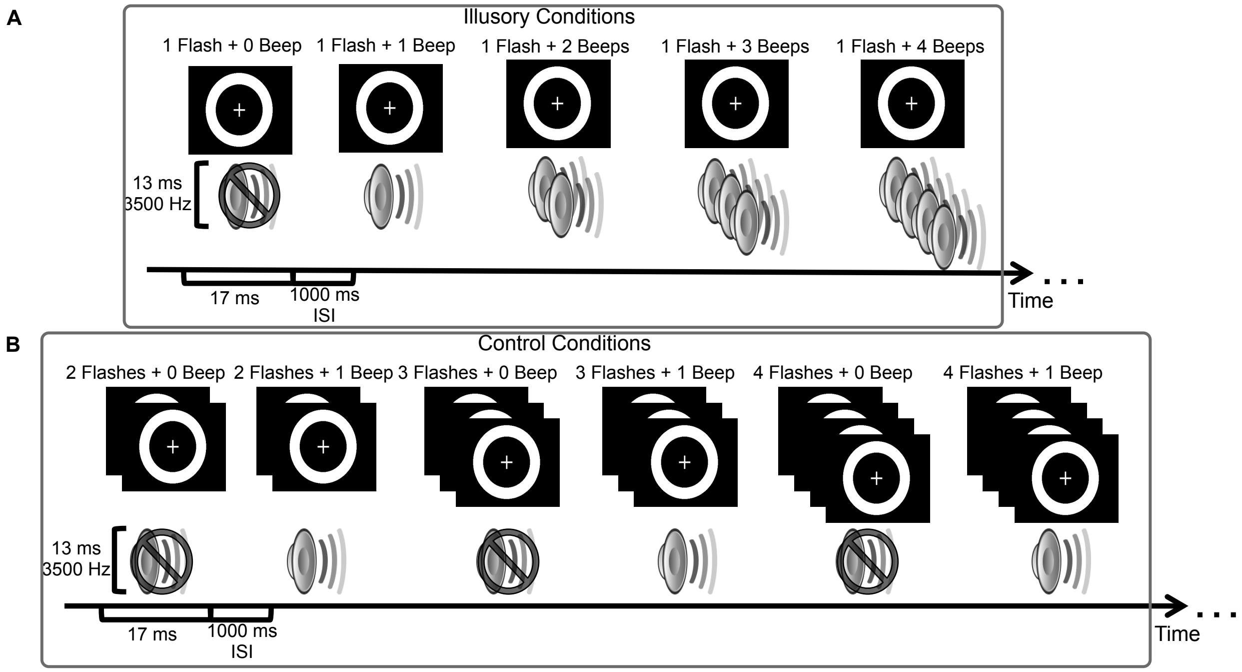

Figure 2.2. A schematic illustration of each of the trial types in the double flash illusion. A. Illusory conditions where each single-flash presentation of a visual stimulus (1 flash) was paired with 0, 1, 2, 3 or 4 auditory stimuli (0, 1, 2, 3, 4 beeps). B. Control conditions where 2 or 3 flash presentations of a visual stimulus (2, 3, 4 flashes) were paired with 0 or 1 auditory stimuli (0, 1 beep).

Procedure

Participants sat 60 cm from a 21.5” computer screen in a dimly lit testing room. Auditory stimuli were presented using *Sony Studio Monitor Series* noise cancelling headphones placed over the ears with the volume regulated to a comfortable hearing level by the participant. In Experiment 1 (temporal binding window), participants were instructed to respond as quickly and as accurately as possible, whether the auditory and visual stimuli were presented at the same time or at different times, using designated keys on a keyboard. In Experiment 2 (double flash illusion), participants were instructed to respond as quickly and as accurately as possible, by using the number pad on a keyboard, how many visual ring flashes they perceived (1, 2, 3, 4). The clock measuring reaction times was started at the onset of the first stimulus presented in each trial. Participants were given verbal instructions and a short practice session for familiarization with the task.

Results

Experiment 1: Temporal binding window

Reaction Time

A 2 × 3 repeated measures analysis of variance (ANOVA) comparing condition (left window (auditory stimulus preceding visual; AV) vs. right window (visual stimulus preceding auditory; VA)) and group (ME vs. BV vs. MV) revealed no significant interaction, $F(2, 45) = 0.160$, $p = 0.852$, $ŋ_{p}^{2} = 0.007$. There was a significant main effect of participant group, $F(2, 45) = 4.819$, $p = 0.013$, $ŋ_{p}^{2} = 0.176$ and main effect of condition, $F(1, 45) = 4.101$, $p = 0.049$, $ŋ_{p}^{2} = 0.084$. Bonferroni corrected pairwise comparisons indicate that the ME group had significantly longer reaction times compared to the BV group (left: $p = 0.011$; right: $p = 0.015$) but not MV group. Figure 2.3 plots the reaction time for each BV, MV and ME groups.

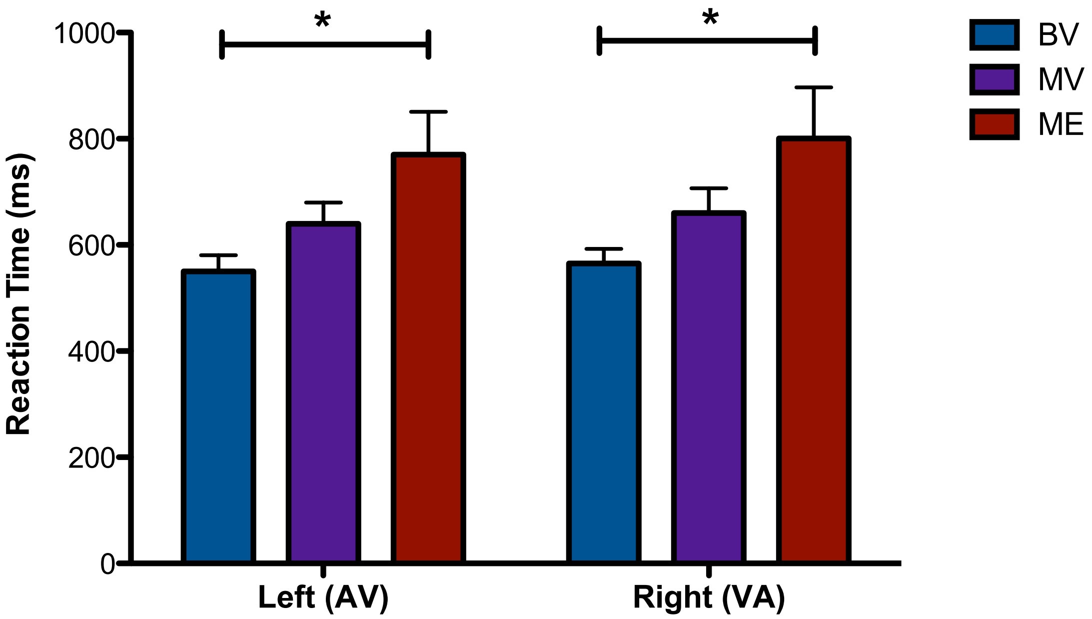

Figure 2.3. The reaction time (ms) for each of the binocular viewing (BV, blue), monocular-viewing (MV, purple) and monocular enucleation (ME, red) groups for the left (AV: auditory stimulus preceding visual) and right (VA: visual stimulus preceding auditory) SOA. Error bars represent standard error of the mean (SEM).

Width of temporal binding window

The widths of the TBW's were calculated based on the responses of whether the participants perceived the flash and beep to occur at the same time (simultaneous) or at a different time (not simultaneous). All data were plotted as the proportion perceived "simultaneous" at each SOA. Data were fit with 2 psychometric sigmoid functions, one for the left (AV: auditory stimulus preceding visual) and right (VA: visual stimulus preceding auditory) windows. Each participant's point of subjective simultaneity (PSS) was estimated based on the 50% rate of perceived simultaneity y-value for best-fit sigmoid (Stevenson, Zemtsov & Wallace, 2012).

A 2 × 3 repeated measures ANOVA comparing condition (left window vs. right window) and group (ME vs. BV vs. MV) revealed no significant interaction, $F(2, 42) = 0.355$, $p = 0.703$, $ŋ_{p}^{2} = 0.017$ and no main effect of participant group, $F(2, 42) = 1.747$, $p = 0.187$, $ŋ_{p}^{2} = 0.077$. There was a significant main effect of condition, $F(1, 42) = 4.519$, $p = 0.039$, $ŋ_{p}^{2} = 0.097$. Bonferroni corrected pairwise comparisons indicate that there was no difference in width of the temporal binding window between the ME, MV and BV groups. Figure 2.4 plots the width of the temporal binding window for the BV, MV and ME groups.

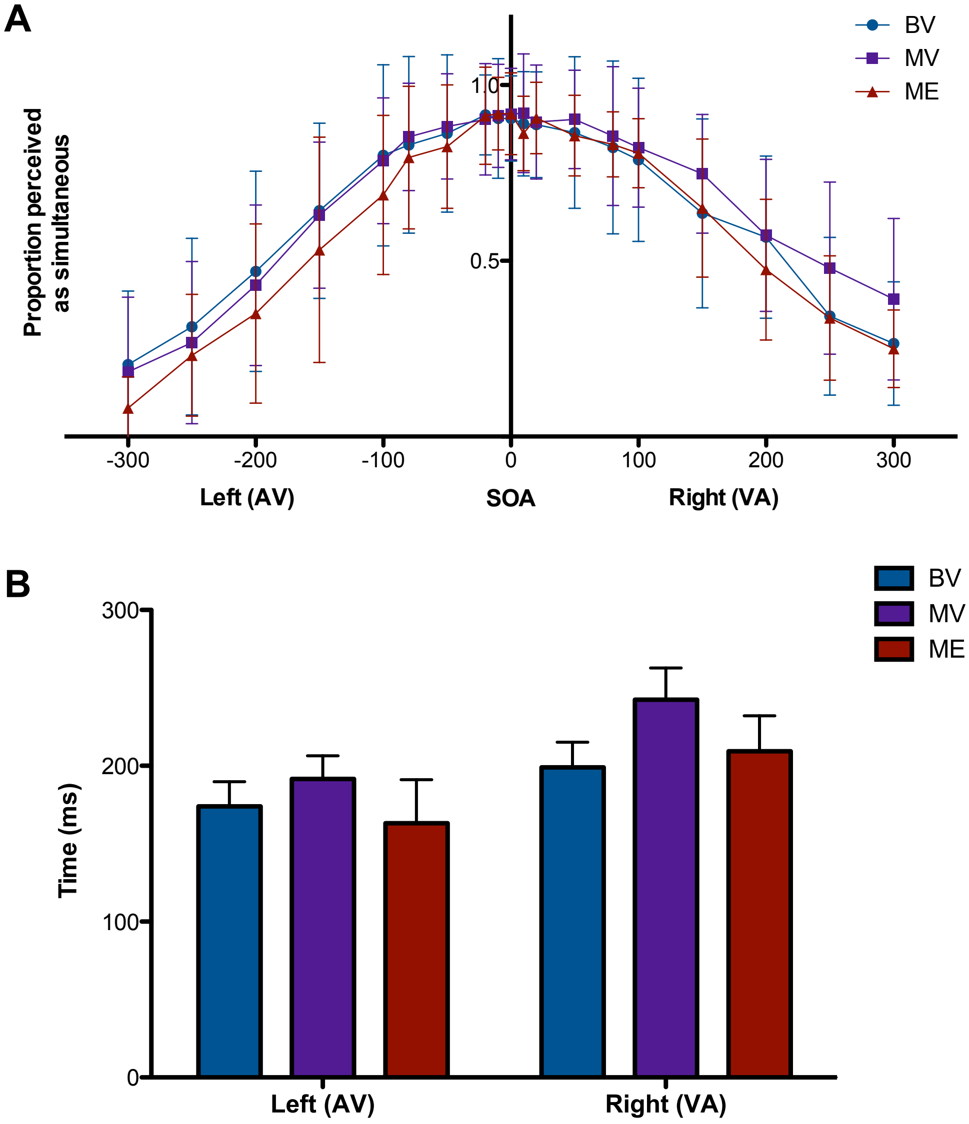

Figure 2.4. The mean proportion of stimuli perceived as “simultaneous” at each SOA for each participant group (BV, blue; MV, purple; ME, red). B. The width of the temporal binding window (ms) for each of the binocular viewing (BV, blue), monocular-viewing (MV, purple) and monocular enucleation (ME, red) groups for the left (AV: auditory stimulus preceding visual) and right (VA: visual stimulus preceding auditory) SOAs. Error bars represent standard error of the mean (SEM).

Experiment 2: Double flash illusion

Reaction time

A 5 x 3 repeated measures ANOVA comparing group (ME vs. BV vs. MV) and reaction times for the double flash illusion conditions (1 flash + 0 beep, 1 flash + 1 beep, 1 flash + 2 beeps, 1 flash + 3 beeps, 1 flash + 4 beeps) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(9) = 19.887$, $p = 0.019$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.824$) was used. There was no significant interaction, $F(8, 180) = 0.632$, $p = 0.719$, $\eta_p^2 = 0.027$ or main effect of participant group, $F(2, 45) = 0.595$, $p = 0.556$, $\eta_p^2 = 0.026$. There was, however, a main effect of condition, $F(4, 180) = 5.545$, $p = 0.001$, $\eta_p^2 = 0.110$. Bonferroni corrected pairwise comparisons indicate that there was no difference in reaction time between the ME, MV, and BV groups.

A 6 × 3 repeated measures ANOVA comparing group (ME vs. BV vs. MV) and reaction time for bimodal control conditions (2 flashes + 0 beep, 2 flashes + 2 beep, 3 flashes + 0 beep, 3 flashes + 2 beep, 4 flashes + 0 beep, 4 flashes + 1 beep) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(14) = 29.536$, $p = 0.009$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.797$) was used. There was no significant interaction, $F(10, 225) = 0.897$, $p = 0.520$, $\eta_p^2 = 0.038$, main effect of participant group, $F(2, 45) = 1.674$, $p = 0.199$, $\eta_p^2 = 0.069$ or main effect of condition, $F(5, 225) = 0.366$, $p = 0.832$, $\eta_p^2 = 0.008$. Bonferroni corrected pairwise comparisons indicate that there was no difference in reaction time between the ME, MV, and BV groups for the control conditions. Figure 2.5 plots reaction time for each of the BV, MV and ME groups.

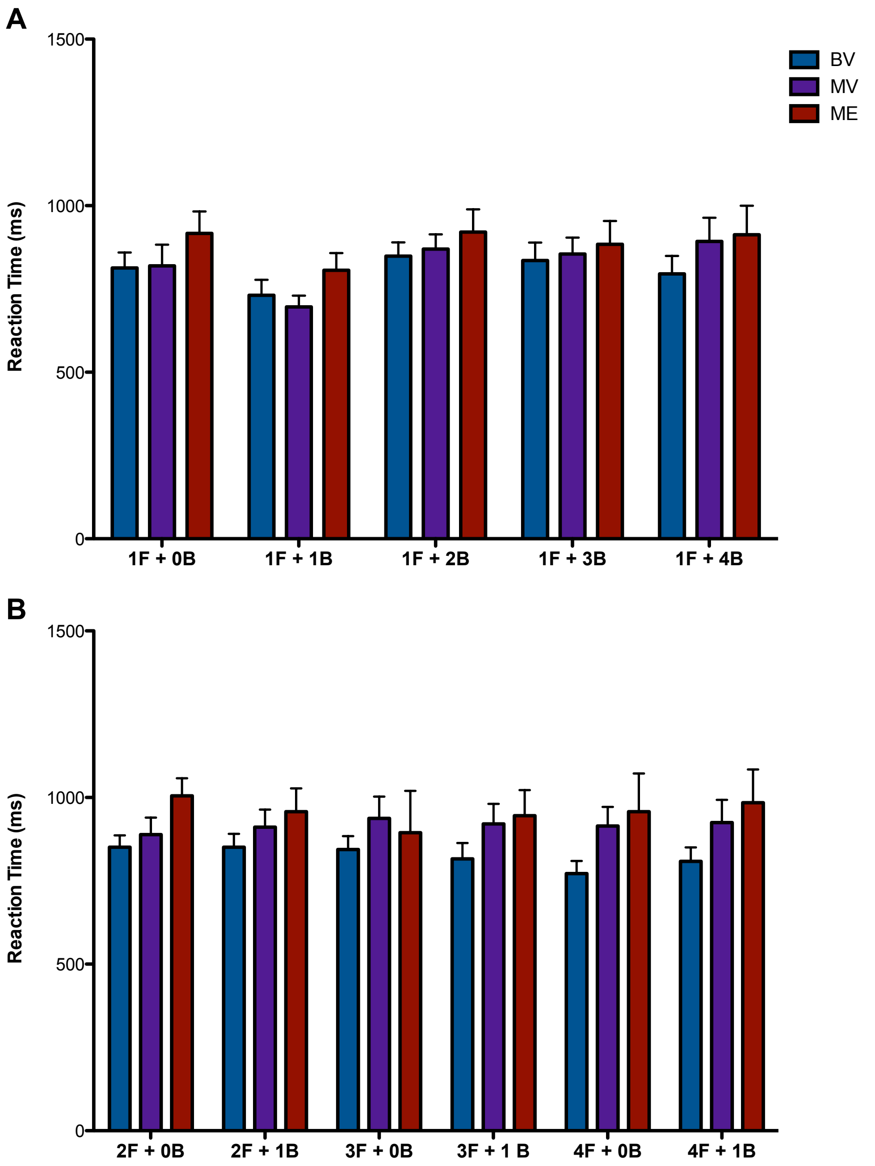

Figure 2.5. The reaction time (ms) for each of the binocular viewing (BV, blue), monocular-viewing (MV, purple) and monocular enucleation (ME, red) groups. A. Each single-flash presentation of a visual stimulus (1F) was paired with 0, 1, 2, 3 or 4 auditory stimuli (0B, 1B, 2B, 3B, 4B). B. Control conditions where 2 or 3 flash presentations of a visual stimulus (2F, 3F, 4F) were paired with 0 or 1 auditory stimuli (0B, 1B). Error bars represent standard error of the mean (SEM).

Measure of double flash illusion

A 5 × 3 repeated measures ANOVA comparing group (ME vs. BV vs. MV) and double flash illusory conditions (1 flash + 0 beep, 1 flash + 1 beep, 1 flash + 2 beeps, 1 flash + 3 beeps, 1 flash + 4 beeps) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(9) = 143.048$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.390$) was used. There was a significant interaction, $F(8, 180) = 3.907$, $p = 0.011$, $\eta_p^2 = 0.148$; significant main effect of participant group, $F(2, 45) = 4.165$, $p = 0.022$, $\eta_p^2 = 0.156$ and significant main effect of condition, $F(4, 180) = 33.959$, $p < 0.001$, $\eta_p^2 = 0.430$. Bonferroni corrected pairwise comparisons indicate that the BV group perceived more flashes than the MV (2 beeps: $p= 0.040$, 3 beeps: $p= 0.020$ and 4 beeps: $p= 0.007$) and the ME (2 beeps: $p= 0.029$, 3 beeps: $p= 0.043$ and 4 beeps: $p= 0.017$) groups. Furthermore, the ME group showed no difference between conditions (0 beeps vs. 1 beep vs. 2 beeps vs. 3 beeps vs. 4 beeps) whereas, both BV and MV groups perceived more flashes during the illusory conditions (BV: 0 beeps vs. 2 beeps $p < 0.001$; 0 beep vs. 3 beeps $p < 0.001$; 0 beep vs. 4 beeps $p < 0.001$; 1 beep vs. 2 beeps $p < 0.001$, 1 beep vs. 3 beeps $p < 0.001$, 1 beep vs. 4 beeps $p < 0.001$) (MV: 0 beep vs. 2 beeps $p < 0.001$; 0 beep vs. 3 beeps $p = 0.05$; 0 beep vs. 4 beeps $p= 0.022$; 1 beep vs. 2 beeps $p = 0.001$, 1 beep vs. 3 beeps $p= 0.007$, 1 beep vs. 4 beeps $p= 0.002$) compared to the non-illusory conditions (0 beep and 1 beep).

A 6 × 3 repeated ANOVA comparing group (ME vs. BV vs. MV) and bimodal condition (2 flashes + 0 beep, 2 flashes + 2 beep, 3 flashes + 0 beep, 3 flashes + 2 beep, 4 flashes + 0 beep, 4 flashes + 1 beep) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(14) = 117.271$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.422$) was used. There was no significant interaction, $F(10, 225) = 0.305$, p

= 0.883, η_p^2 = 0.013 or main effect of participant group, $F(2, 45) = 1.737$, $p = 0.188$, η_p^2 = 0.072. There was a significant main effect of condition, $F(5, 225) = 176.326$, $p < 0.001$, η_p^2 = 0.797. Bonferroni corrected pairwise comparisons indicate that there was no difference in reaction time between the ME, MV, and BV groups for the control conditions. Figure 2.6 plots a measure of the double flash illusion and control conditions for each for the BV, MV and ME groups.

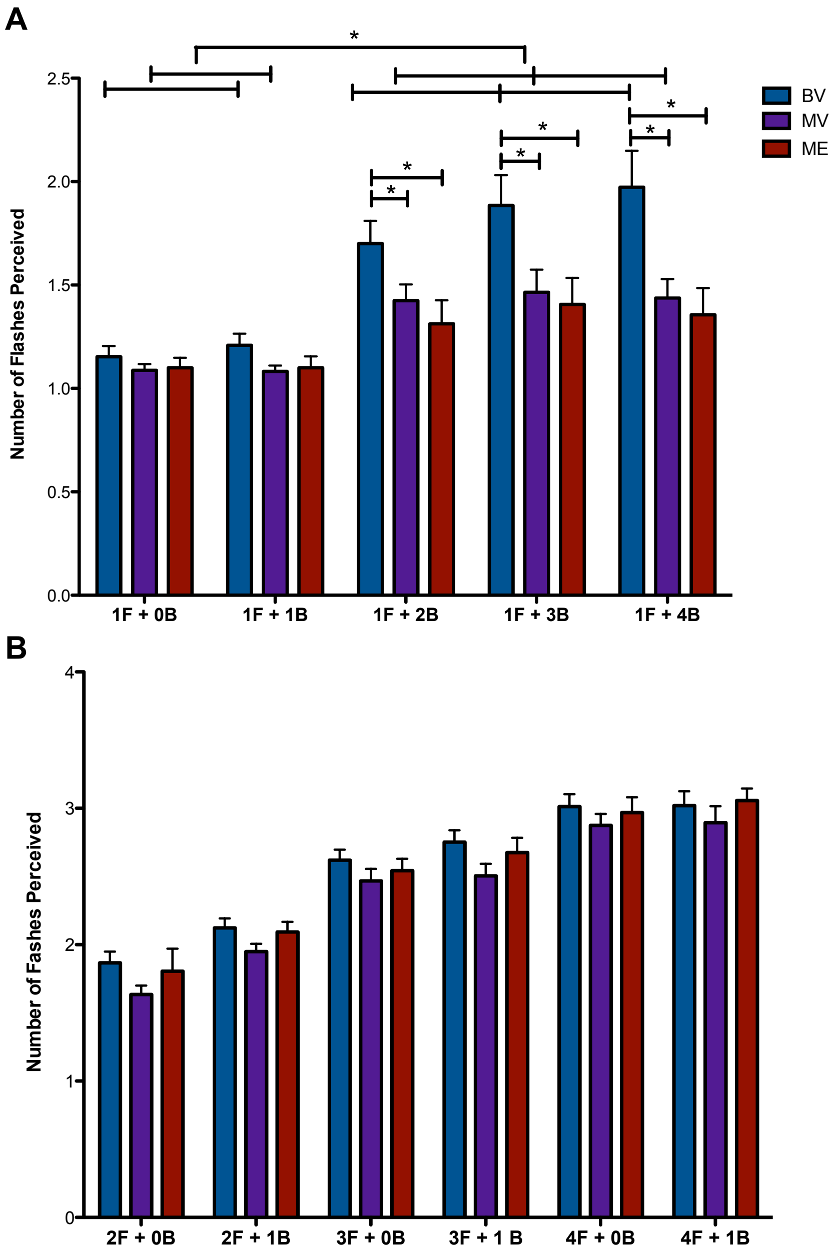

Figure 2.6. The number of flashes perceived for each of the binocular viewing (BV, blue), monocular-viewing (MV, purple) and monocular enucleation (ME, red) groups. A. Each single-flash presentation of a visual stimulus (1F) was paired with 0, 1, 2, 3 or 4 auditory stimuli (0B, 1B, 2B, 3B, 4B). B. Control condition where 2 - 4 flash presentations of a visual stimulus (2F, 3F, 4F) were paired with 0 or 1 auditory stimuli (0B, 1B). Error bars represent standard error of the mean (SEM).

Correlation of the temporal binding window and double flash illusion

Correlations were calculated comparing TBW width and number of flashes perceived in the double flash illusion for the 1 flash + 0 beep, 1 flash + 1 beep, 1 flash + 2 beeps, 1 flash + 3 beeps, 1 flash + 4 beeps conditions for each individual's left (AV) and right (VA) TBW. To account for multiple comparisons, a Bonferroni correction was conducted ($\alpha = 0.01$). No significant correlations were observed for any of the double flash conditions with either the left or right TBWs for any of the participant groups. Figures 2.7, 2.8 and 2.9 present the statistics of the correlations for each double flash illusion condition for the BV, MV and ME groups respectively.

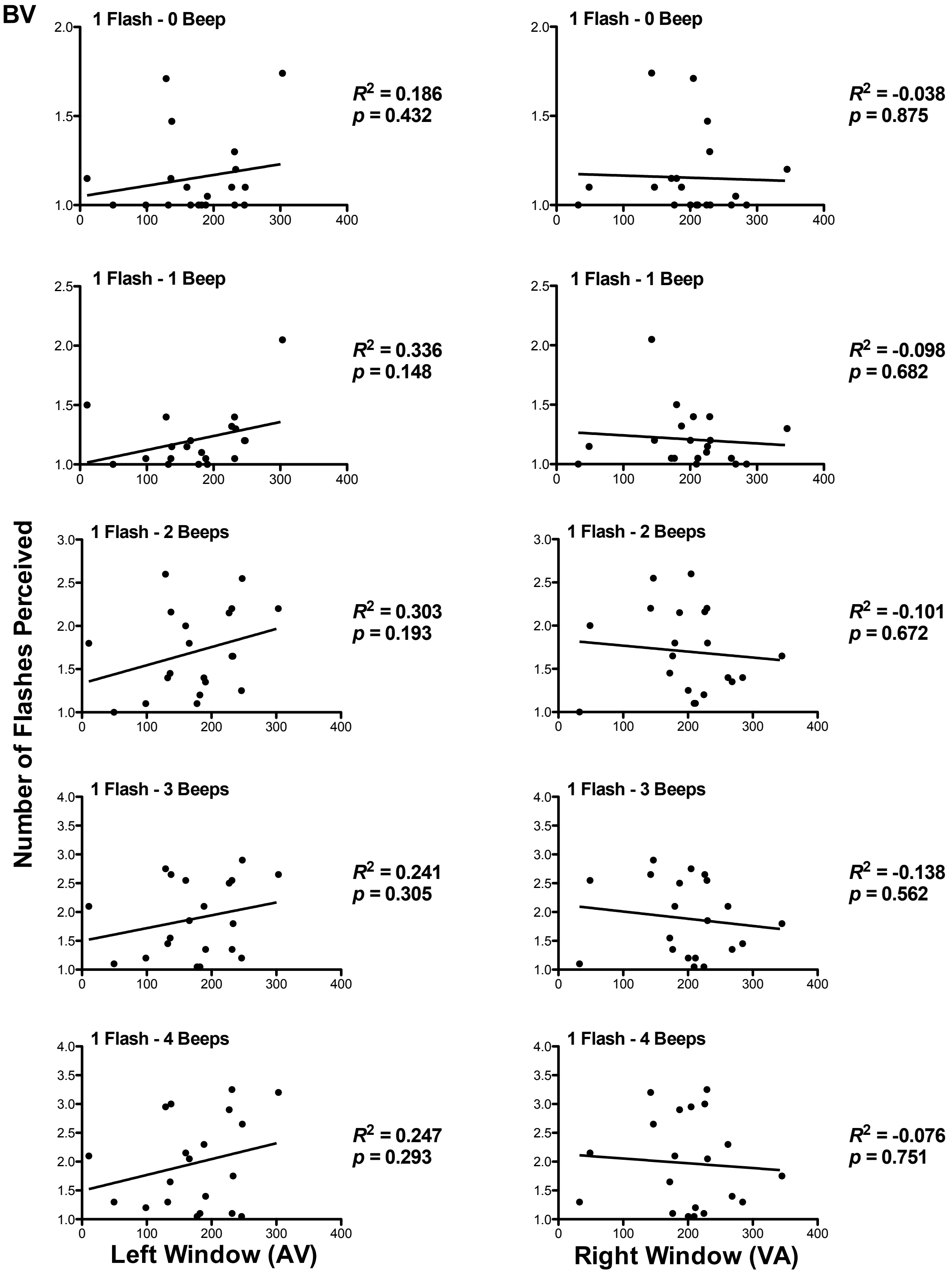

Figure 2.7. Correlations between the perceived number of flashes during the double flash illusion experiment for the 0, 1, 2, 3 and 4 beep conditions and the left and right TBW width for the binocular viewing control group.

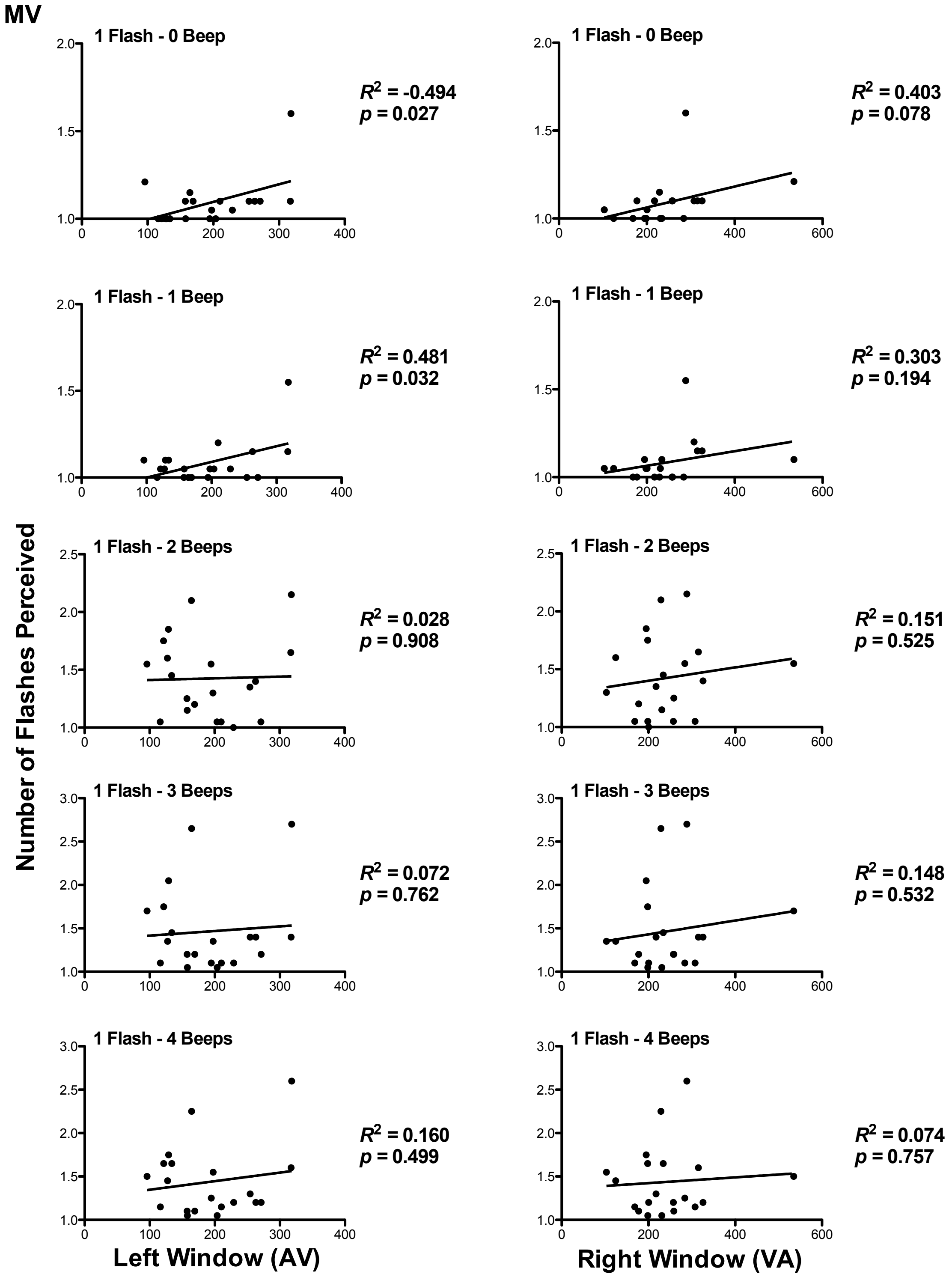

Figure 2.8. Correlations between the perceived number of flashes during the double flash illusion experiment for the 0, 1, 2, 3 and 4 beep conditions and the left and right TBW width for the monocular viewing control group.

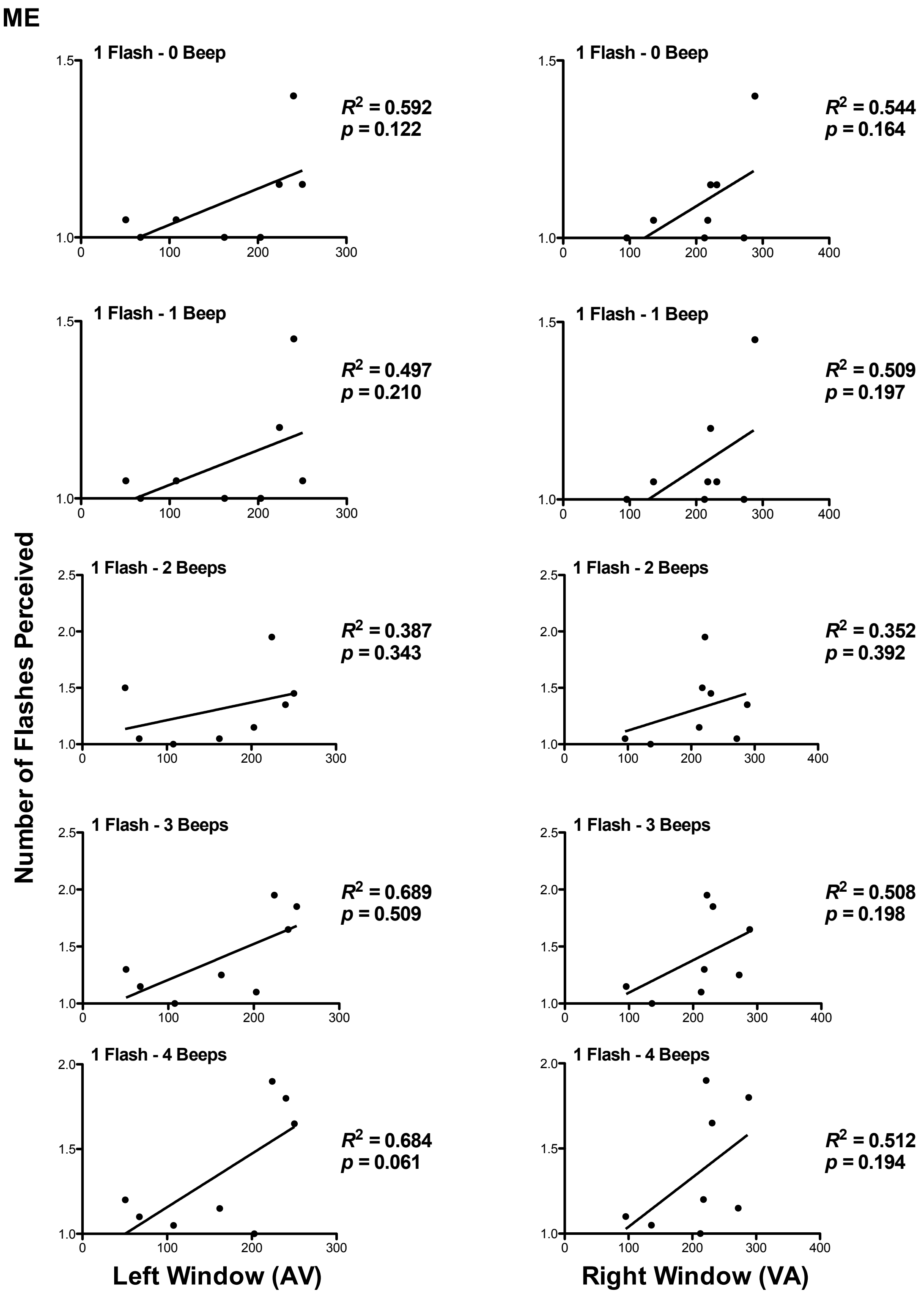

Figure 2.9. Correlations between the perceived number of flashes during the double flash illusion experiment for the 0, 1, 2, 3 and 4 beep conditions and the left and right TBW width for the people with one eye.

Discussion

The current study investigated whether losing one eye early in life impacted the temporal binding window of simple audiovisual stimuli and its relation to the susceptibility of the double flash illusion. In Experiment 1, people with one eye did not differ in the width of their temporal binding window compared to binocular and monocular viewing controls. However, people with one eye had longer response latencies compared to binocular viewing controls. Monocular viewing controls' response latencies were intermediate to the two other groups. In Experiment 2, people with one eye were not as susceptible to the double flash illusion compared to both binocular and monocular viewing controls. Additionally, monocular viewing controls experienced a reduction in the perception of the double flash illusion compared to binocular viewing controls. In this task, people with one eye responded as quickly as binocular and monocular viewing controls. Taken together, these results suggest that susceptibility to the double flash illusion may not simply reflect the width of the temporal binding window. Furthermore, these results provide evidence that people with one eye demonstrate adaptation for audiovisual integration due to the reduction of visual input from one eye.

The temporal and spatial relationship of auditory and visual events with one another are important principles of multisensory integration, where more spatially and temporally congruent auditory and visual stimuli are more likely to be perceived as one event (Stevenson et al., 2012b). In the spatial domain, the integration of low-level auditory and visual events is no different for people with one eye compared to controls despite slower reaction times in this group (Moro, Harris & Steeves, 2014). The current results reflect the same pattern of intact performance despite slower reaction times except that the present findings reflect the temporal domain. It is likely that the altered ability to process low-level sensory information results in slower reaction times in order to achieve optimal performance during audiovisual integration that is similar to control groups. The resulting slower reaction time may serve as an adaptive strategy since the misperception of even low-level sensory information can be maladaptive. This is evident in other clinical populations specifically individuals with autism spectrum disorder (ASD; Foss-Feig et al., 2010; Kwakye et al., 2011; Taylor, Isaac & Milne, 2010) who have larger temporal binding windows which results in the erroneous integration of auditory and visual events that do not come from the same source. An alternative account for the slower reaction times observed in this study could be due to altered wiring for these pathways within the brain. Our group has recently observed altered white matter tracts in the visual and auditory systems that could account for longer processing times in this patient group (Wong et al., 2017).

It has been shown that individual differences in the perception of temporally synchronous audiovisual stimuli reflect the susceptibility of audiovisual illusions. Stevenson and colleagues (2012a) compared individuals’ TBW to their performance on the double flash illusion hypothesizing that a narrower temporal binding window will result in an increased ability to dissociate asynchronous sensory signals and greater enhancements associated with integration of synchronous sensory input. Their findings confirmed this hypothesis where individuals with narrower TBWs were more temporally precise and subsequently failed to integrate asynchronous stimuli and therefore were less susceptible to the double flash illusion (Stevenson et al., 2012a). The current results stand in contrast to this hypothesis since susceptibility to the double flash illusion was not correlated with width of the temporal binding window for any of the participant groups. Furthermore, people with one eye did not differ in width of TBW compared to binocular and monocular viewing controls, however, they were not susceptible to the double flash illusion. This indicates that people with one eye did not erroneously integrate asynchronous stimuli, despite not having a more precise TBW compared to controls. Given the current results indicating a lack of double flash illusion, one might expect people with one eye to have a narrower TBW compared to controls. It is possible that separate processing mechanisms are used to perceive illusory audiovisual and congruent audiovisual pairings, where the mismatched unimodal stimuli require an additional mechanism to overcome their disparity (Alsius, Paré & Munhall, 2017; Green & Kuhl, 1991; Massaro & Cohen, 1983; Romero et al., 2015). These results are consistent with our previous research showing people with one eye process audiovisual information differently compared to binocular viewing controls (Moro & Steeves, 2012; 2013).

Furthermore, it is also likely that attention modulates the perception of the double flash illusion. Attention contributes to and interacts with perception and plays a role in the way in which people view bimodal stimuli (see Alais, Newell & Mamassian, 2017; Harris & Jenkin, 2001 for a review). Since people with one eye have a 50% reduction of the visual input to their brain, it is possible attention is redirected towards their individual unimodal sensory inputs, especially during ambiguous multisensory presentations, in an attempt to better understand the complex multisensory information in the world. This attentional shift might result in a reduction in the perception of audiovisual illusions as demonstrated in this current study and previous studies showing a lack of visual dominance (Moro & Steeves, 2012; 2013). Controls viewing with an eye patch were susceptible to the double flash illusion, however, to a lesser extent than binocular viewing controls. This indicates that short-term visual deprivation from the eye-patch over one eye at the time of testing which results in a transient reduction of vision may also modify attentional resources thereby affecting the susceptibility to the double flash illusion. Future research directly investigating the influence of attention in people with one eye and monocular viewing controls, as well as, testing the same participants in both control groups and comparing the change in performance would contribute useful evidence to this emerging question.

In conclusion, people with one eye appear to have an altered ability to process sensory information, likely as an adaptation for their loss of visual input. People with one eye do not differ in width of their TBW but had longer reaction times and were not susceptible to the double flash illusion compared to binocular and monocular viewing controls. These results contribute to the likelihood that accommodations result in slower reaction times and altered attentional focus. These accommodations for audiovisual processing are unique to people with one eye since they do not show the same relationship between audiovisual integration factors and susceptibility to illusions. This may serve as an adaptive compensatory mechanism for the loss of half of the visual input to the brain during development.

Acknowledgements

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CHAPTER III

INTACT DYNAMIC VISUAL CAPTURE IN PEOPLE WITH ONE EYE[2]

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[2] Moro, S. S. & Steeves, J. K. E. (in press). *Multisensory Research*. DOI: 10.1163/22134808-20181311.

Abstract

Observing motion in one modality can influence the perceived direction of motion in a second modality (dynamic capture). For example observing a square moving in depth can influence the perception of a sound to increase in loudness. The current study investigates whether people who have lost one eye are susceptible to audiovisual dynamic capture in the depth plane similar to binocular and eye-patched viewing control participants. Partial deprivation of the visual system from the loss of one eye early in life results in changes in the remaining intact senses such as hearing. Linearly expanding or contracting discs were paired with increasing or decreasing tones and participants were asked to indicate the direction of the auditory stimulus. Magnitude of dynamic visual capture was measured in people with one eye compared to eye patched and binocular viewing controls. People with one eye have the same susceptibility to dynamic visual capture as controls, where they perceived the direction of the auditory signal to be moving in the direction of the incongruent visual signal, despite previously showing a lack of visual dominance for audiovisual cues. This behaviour may be the result of directing attention to the visual modality, their partially deficient sense, in order to gain important information about approaching and receding stimuli which in the former case could be life-threatening. These results contribute to the growing body of research showing that people with one eye display unique accommodations with respect to audiovisual processing that are likely adaptive in each unique sensory situation.

Many different sensory stimuli are available to our sensory systems as we move about our day. We typically use information presented to us to our full advantage if all of our sensory systems are intact. In the case of people who have had their visual input reduced by half, specifically people with only one eye, it seems reasonable to expect that other intact sensory systems should function to the best of their ability or perhaps even better in order to adapt and compensate for the partial loss of vision.

Unilateral eye enucleation (the surgical removal of one eye) is a unique model for examining the consequences of the loss of binocularity (see Steeves, Gonzalez & Steinbach, 2008, for a review). Unilateral eye enucleation is unlike other forms of monocular visual deprivation, such as cataract or strabismus, that leave abnormal visual input, since removing the eye completely eliminates all forms of visual input to the brain from that eye (Steeves et al., 2008). In fact removing an eye early in life during postnatal visual development results in enhanced visual spatial abilities (reviewed in Steeves et al., 2008). People with one eye have heightened sensitivity to line orientation (Reed, Steinbach, Ono, Kraft & Gallie, 1995), superior contrast sensitivities at 2, 4, and 8 cycles/degree (Nicholas, Heywood & Cowey, 1996), intact and sometimes enhanced ability recognize objects such as texture defined letters (Steeves, González, Gallie & Steinbach, 2002), superior foveal acuity for illiterate 'E' optotypes at 96%, 13.5% and 4.7% contrasts (González, Steeves, Kraft, Gallie & Steinbach, 2002), enhanced discrimination of low-contrast global shape (Steeves, Wilkinson, Gonzalez, Wilson & Steinbach, 2004) and intact Snellen acuity and enhanced Vernier acuity (Freeman & Bradley, 1980).

In contrast to these enhancements in visual spatial processing, reduced or altered visual function for visual motion processing has been demonstrated in people who have had an eye removed early in life likely due to the inherent link between binocularity and motion processing during visual maturation (reviewed in Steeves et al., 2008). Overall, motion-defined letter recognition is impaired compared to controls (Steeves et al., 2002). People with one eye do not differ from controls in sensitivity to the relative motion of shearing texture, however they do show reversed velocity discrimination biases compared to binocular viewing controls (Bowns, Kirshner & Steinbach, 1994). This reversed bias was attributed to potential compensation for the lack of binocular disparity information (a binocular cue to depth) by attempting to use motion parallax (a monocular cue to depth) to calculate depth perception (Bowns, Kirshner & Steinbach, 1994). In addition, people with one eye have shown impairments in the perception of time to collision of an approaching object (Steeves, Gray, Steinbach & Regan, 2000). Time to collision is overestimated in people with one eye but underestimated in binocular controls affecting the ability of people with one eye to correctly perceive motion in depth (Steeves, Gray, Steinbach & Regan, 2000).

There is a growing body of evidence indicating that people with one eye adaptively compensate for their 50% loss of visual input to the brain during auditory and audiovisual sensory processing. People with one eye have more accurate auditory localization in the frontal plane (i.e., within 78 degrees to the left or right of straight ahead) except for the extreme periphery (90 degrees left or right) compared to control participants who were monocular viewing, binocular viewing or with their eyes closed (Hoover et al., 2012). People with one eye do not show the typical pattern of visual dominance commonly observed in binocularly intact individuals (Colavita, 1974; Egeth & Sager, 1977; Colavita & Weisberg, 1979; Sinnett et al., 2008; Spence, 2009; Spence, Parise & Chen, 2011) and instead demonstrate equivalent auditory and visual processing (Moro & Steeves, 2012; 2013). They have optimal audiovisual spatial integration with respect to the variance of audiovisual localization compared to control groups (Moro et al., 2014). Despite optimal audiovisual spatial integration, people with one eye take longer to localize visual compared to auditory stimuli (Moro et al., 2014) possibly due to plastic changes in wiring of the visual system following eye enucleation (Wong et al, 2017). Overall, people with one eye appear to advantageously alter their ability to process auditory and audiovisual information.

The integration of audiovisual moving stimuli is important given that many audiovisual events are dynamic and can be crucial for survival, such as in the case of an object rapidly approaching your body (Graziano & Cooke, 2006; Bach et al., 2008; see Soto-Faraco et al., 2003 for review). The depth plane is particularly important since the rapid detection of looming motion can signal the approach of a potentially threatening object and the accurate detection of receding motion can signal its retreat (Harrison, 2012). Cappe and colleagues (2009) demonstrated that audiovisual looming stimuli affect both reaction times and subjective experience of the stimuli. Through the presentation of visual stimuli in the form of expanding disks paired with auditory stimuli that increased or decreased in intensity, reaction time performance was selectively facilitated in multisensory conditions that contained congruent audiovisual looming stimuli compared to the other stimuli combinations (Cappe et al., 2009). Furthermore, a significant negative correlation was observed where faster reaction times suggested a decreased strength of perception of movement (calculated by finding the ratio of the difference of movement ratings between the multisensory condition and the best constituent unisensory condition relative to the best unisensory condition) (Cappe et al., 2009). These results indicate that participants who demonstrate faster reaction times may make less perceptual gains in their subjective experience of the stimuli during multisensory presentations since they already have a strong unisensory perception of movement (Cappe et al., 2009).

Both the visual and auditory modalities can provide reliable information about looming and receding motion (Harrison, 2012). Adaptation of motion in one modality can influence the perceived direction of motion in a second sensory modality (Jian et al., 2008; Kitagawa & Ichihara, 2002). This can be observed through cross-modal motion adaptation after-effects, where participants who have adapted to viewing a visual stimulus increasing or decreasing in size perceive a constant auditory stimulus to be changing in loudness (Kitagawa & Ichihara, 2002). Dynamic visual capture is a phenomenon where a moving visual stimulus influences the perception of an auditory stimulus. In the depth plane, dynamic visual capture has been shown for both stationary auditory stimuli, that are perceived as moving in the direction of the visual stimulus (Mateef et al., 1985) and dynamic auditory stimuli that are perceived moving in the direction of the visual stimulus even if they are actually moving in the opposite direction (Jian et al., 2008; Kitajima and Yamashita, 1999). Dynamic visual capture of a moving auditory stimulus has been successfully demonstrated in the depth plane using both a binocularly fused square (Kitajima and Yamashita, 1999) and a concentric grating that moves radially inward and outward (Jian et al., 2008). In a study conducted by Harrison (2012) participants were asked to judge the direction of an auditory motion cue (increase or decrease in loudness) presented with a visual looming or receding cue in the form of an expanding or contracting disk. Results replicated those of previous studies indicating a robust dynamic visual capture effect where the perceived direction of a moving auditory stimulus was influenced by an ignored visual stimulus moving in the opposite direction (Harrison, 2012). Furthermore, after ensuring that all stimuli were perceptually equal, looming stimuli were found to illicit a greater degree of dynamic capture compared to receding visual stimuli (Harrison, 2012).

The current study investigates whether people who have lost one eye have the same susceptibility to audiovisual dynamic visual capture in the depth plane as control participants. With the use of linearly expanding or contracting disks paired with increasing or decreasing tones in volume, we quantify the magnitude of dynamic visual capture in people with one eye compared to eye patched and binocular viewing controls. Given the mild impairments to motion processing, specifically, the overestimation of time to collision (Steeves, Gray, Steinbach, & Regan, 2000) and lack of visual dominance (Moro & Steeves, 2012; 2013), we predict that people with one eye will not be susceptible to dynamic visual capture.

Materials and Methods

Participants

People with One Eye (Monocular Enucleation, ME):

Seven adult participants who had undergone monocular enucleation (ME) at The Hospital For Sick Children participated in this study (mean age = 33 years, SD = 14). All ME participants had been unilaterally eye enucleated (5 right eye removed) due to retinoblastoma, a rare childhood cancer of the retina. Age at enucleation ranged from 4 to 66 months (mean age at enucleation = 24 months, SD = 20).

Binocular Viewing Control Participants (BV):

Twenty binocularly intact controls with a mean age of 25 years (SD = 5) were tested while viewing stimuli binocularly.

Patched Viewing Control Participants (MV):

Twenty binocularly intact participants, with a mean age of 24 years (SD = 3), completed the experiments with one eye patched. Participants' non-preferred eye was patched with a semi-opaque eye covering and translucent tape (10 right-eye covered).

No significant difference in participant ages between groups was observed through a non-parametric Kruskal-Wallis test (χ^2= 3.053, p= 0.217, with a mean rank age score of 24.90 for the BV group, 20.70 for the MV group and 20.86 for the ME group). All participants (ME, BV, MV) reported normal hearing and normal or corrected-to-normal acuity as assessed by an EDTRS eye chart (Precision Vision™, La Salle, IL) and wore optical correction if needed. All participants gave informed consent prior to their inclusion in the study, which was approved by the York University Office of Research Ethics.

Stimuli

Visual stimuli consisted of a linearly expanding (from 1° visual angle to 13°) or contracting (from 13° visual angle to 1°) black disk on a white background paired with an increasing (75 dBA to 83 dBA) or decreasing (83 dBA to 75 dBA) triangular waveform tone. Stimuli were presented for a duration of 500 ms using VPixx stimulus presentation software (VPixx Technologies Inc., www.vpixx.com). Stimuli were presented in both unimodal (visual only contracting or expanding disks and auditory only rising or descending tones) and bimodal (audiovisual) trials. Bimodal trials consisted of each expanding (looming) or contracting (receding) visual stimulus paired with an increasing (looming) and decreasing (receding) tone (Figure 3.1). There were a total of 40 trials per condition (congruent audiovisual, incongruent audiovisual, unimodal visual and unimodal auditory) presented in counterbalanced order. A 500 ms interstimulus interval (ISI) consisting of silence and a blank screen was presented between stimulation conditions.

Procedure

Participants sat 60 cm from a 21.5" computer screen in a dimly lit testing room. Auditory stimuli were presented to the participants using *Sony Studio Monitor Series* noise cancelling headphones placed over their ears with the volume regulated to a comfortable hearing level by the participants. All participants were instructed to respond as quickly and as accurately as possible using the arrow buttons on a keyboard to indicate whether the auditory stimulus was approaching or receding regardless of the direction of the visual stimulus with which it was paired. Participants were given verbal instructions and a short practice session for familiarization with the task.

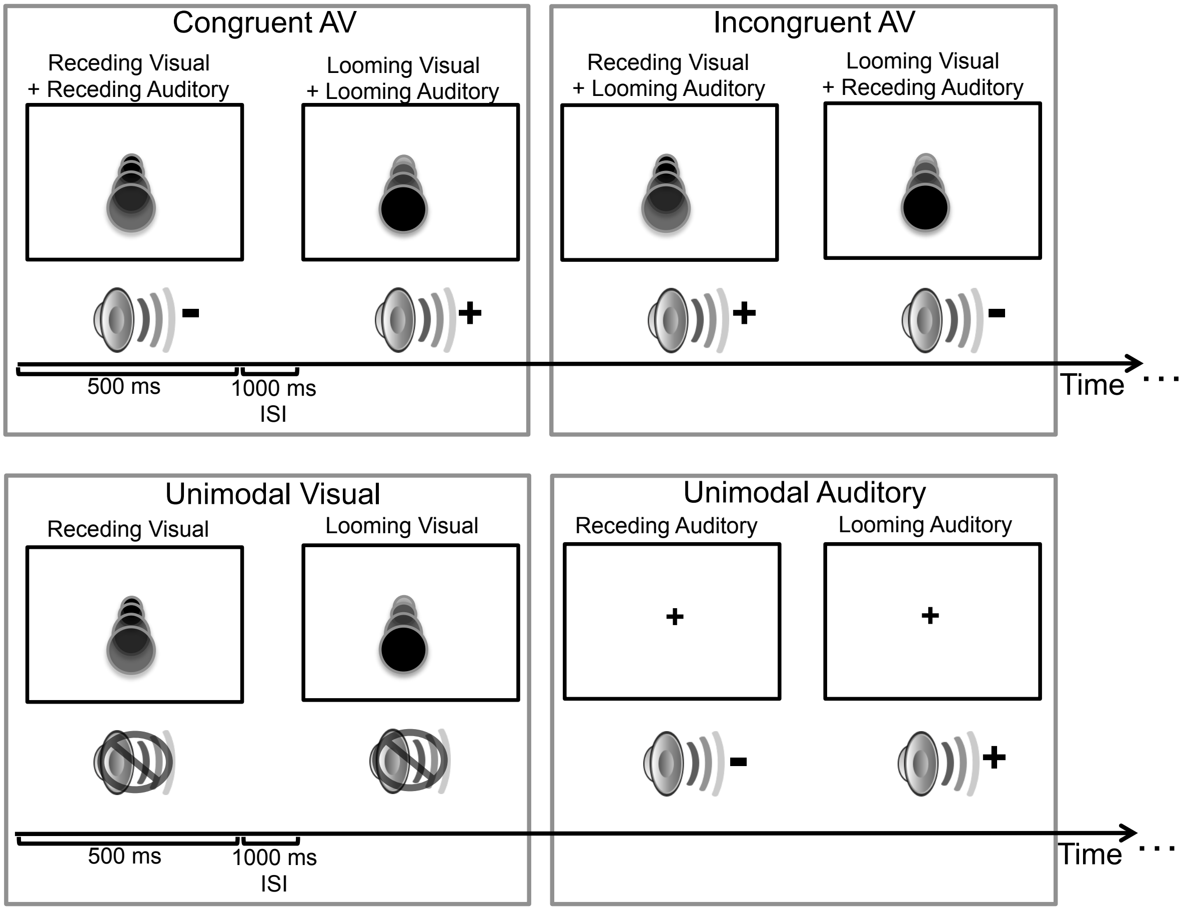

Figure 3.1. A schematic illustration of the presentation of stimuli. The top row depicts audiovisual (AV) trials that were presented either congruently (visual stimulus moving in the same direction as the auditory stimulus) or incongruently (visual stimulus moving in the opposite direction of the auditory stimulus). The bottom row depicts unimodal auditory and unimodal visual conditions that were presented with stimuli moving in both the receding and looming directions.

Results

Reaction time

An 8 × 3 repeated measures analysis of variance (ANOVA) comparing group (ME, BV and MV) and condition (auditory looming, auditory receding, visual looming, visual receding, audiovisual congruent and audiovisual incongruent) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(27) = 92.285$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.624$) was used. There was no significant interaction, $F(14, 308) = 0.835$, $p = 0.582$, $\eta_p^2 = 0.037$ and no main effect of participant group, $F(2, 44) = 0.724$, $p = 0.490$, $\eta_p^2 = 0.032$ for reaction time. There was a main effect of condition, $F(7, 308) = 18.872$, $p < 0.001$, $\eta_p^2 = 0.300$. Audiovisual conditions had longer response times compared to unimodal conditions. There was no difference in reaction time between the groups. Figure 3.2 plots the reaction time for each for the BV, MV and ME groups.

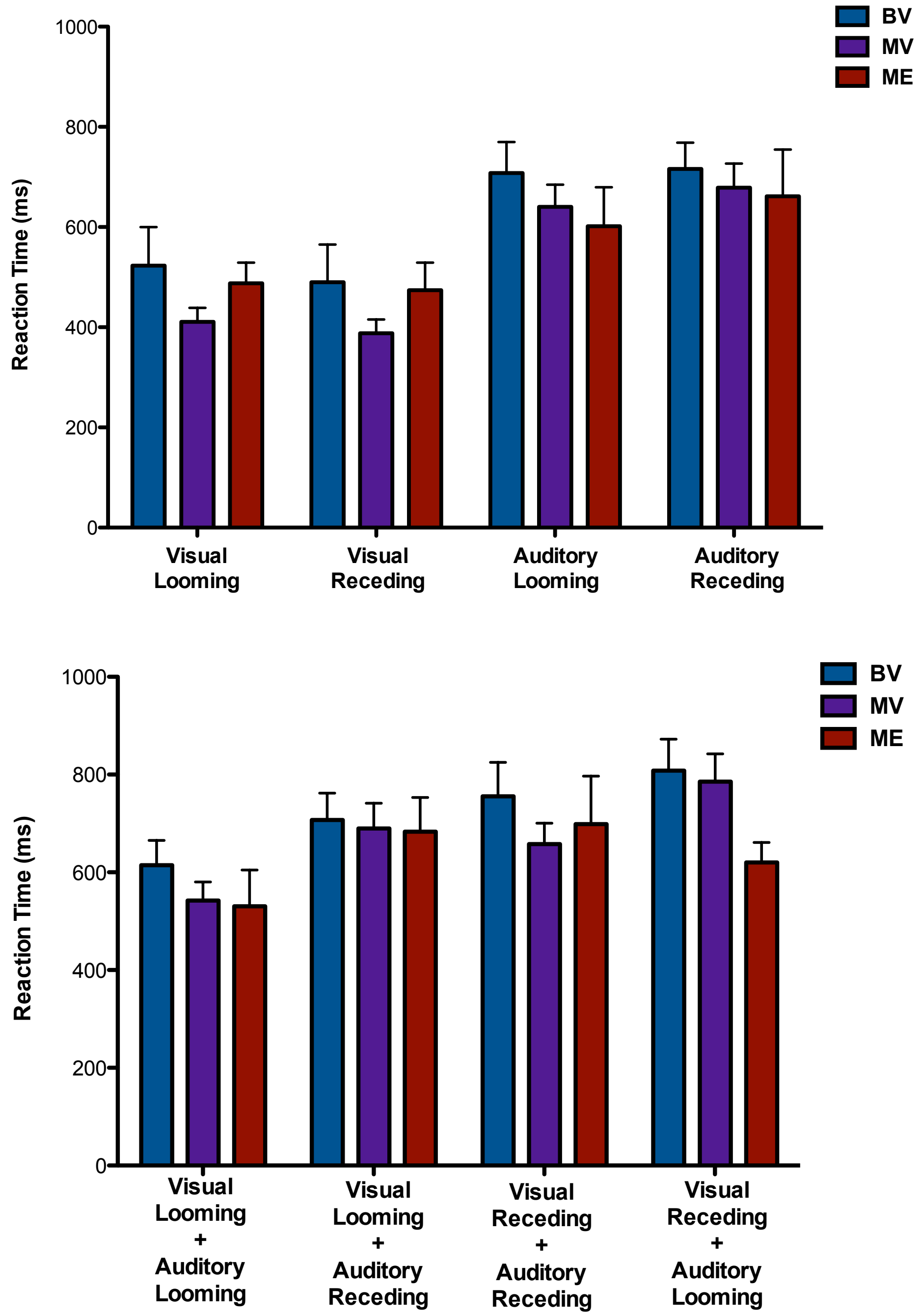

Figure 3.2. The reaction times (ms) for each of the BV (blue), MV (purple) and ME (red) groups for unimodal conditions (top row) and bimodal conditions (bottom row). Error bars represent standard error of the mean.

Accuracy

An 8 × 3 repeated measures analysis of variance (ANOVA) comparing group (ME, BV and MV) and condition (auditory looming, auditory receding, visual looming, visual receding, audiovisual congruent and audiovisual incongruent) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(27) = 260.914$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.444$) was used. There was no significant interaction, $F(14, 308) = 0.264$, $p = 0.956$, $\eta_p^2 = 0.012$ and no main effect of participant group, $F(2, 44) = 2.073$, $p = 0.138$, $\eta_p^2 = 0.086$ for response accuracy. There was a significant main effect of condition, $F(7, 308) = 47.926$, $p < 0.001$, $\eta_p^2 = 0.521$ where less accurate performance was observed in the incongruent audiovisual pairings. In other words, the direction of the auditory signal was more often perceived to be in the direction of the incongruent visual signal. There was no difference in accuracy between the ME group, MV group and BV group. Figure 3.3 plots the accuracy for each for the BV, MV and ME groups.

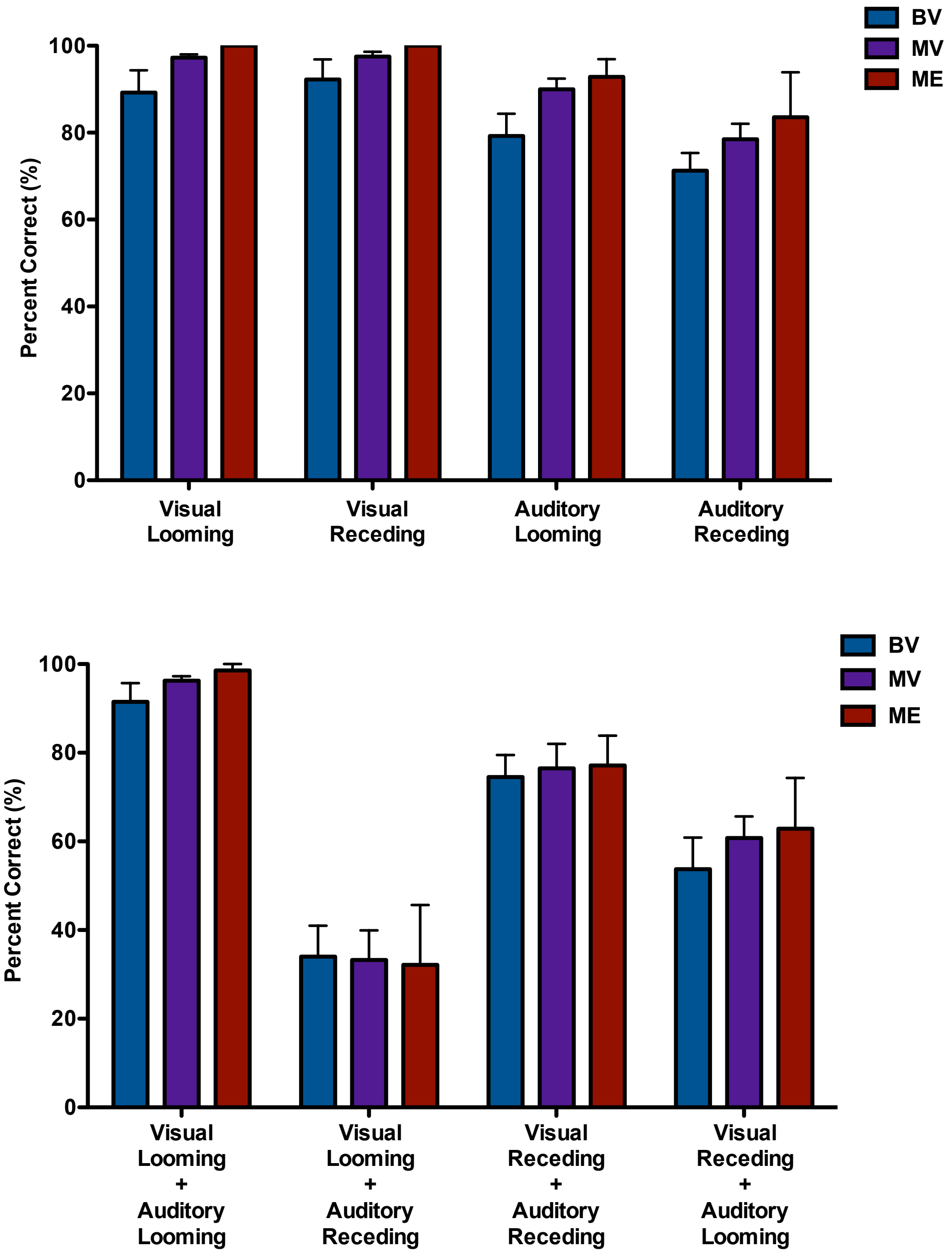

Figure 3.3. Accuracy (percent correct) for each of the BV (blue), MV (purple) and ME (red) groups for unimodal conditions (top panel) and bimodal conditions (bottom panel).

Magnitude of visual capture

Magnitude of visual capture was calculated by subtracting the percentage correct for each bimodal stimulus condition from the corresponding unimodal auditory motion condition (e.g. Unimodal Auditory Looming – Visual Receding Incongruent (bimodal condition consisting of: Visual Receding + Auditory Looming stimulus). A 4 × 3 repeated measures analysis of variance (ANOVA) comparing group (ME, BV and MV) and bimodal condition (visual looming congruent, visual looming incongruent, visual receding congruent and visual receding incongruent) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(5) = 55.051$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.689$) was used. There was no significant interaction, $F(6, 132) = 0.077$, $p = 0.990$, $ŋ_p^2 = 0.004$ or main effect of participant group, $F(2, 44) = 1.393$, $p = 0.259$, $ŋ_p^2 = 0.060$. There was a significant main effect of condition, $F(3, 132) = 32.635$, $p < 0.001$, $ŋ_p^2 = 0.426$ where a larger magnitude of visual capture was observed for incongruent audiovisual stimuli. There was no difference in magnitude of capture between the ME, MV and BV groups. Figure 3.4 plots the magnitude of dynamic capture for each for the BV, MV and ME groups.

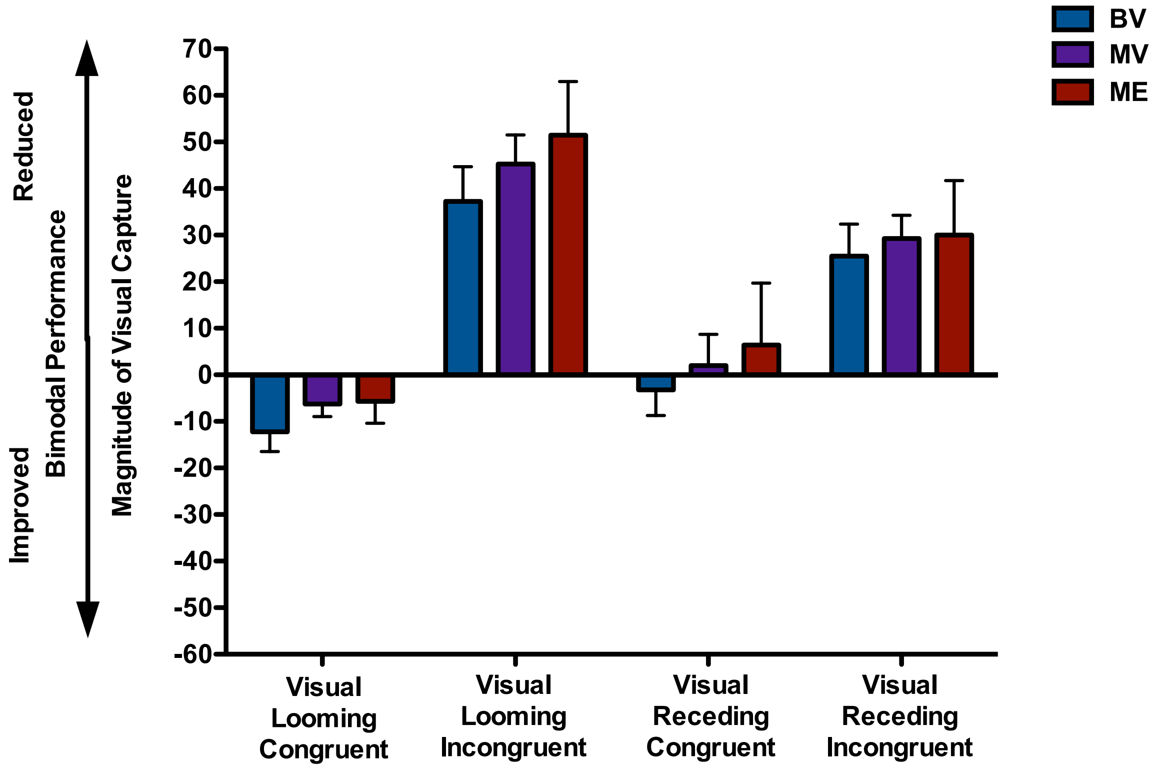

Figure 3.4. Magnitude of dynamic visual capture (difference in accuracy between bimodal cue and corresponding unimodal condition) for each of the BV (blue), MV (purple) and ME (red) groups.

Discussion

The current study investigated whether people who have lost one eye early in life have the same susceptibility to audiovisual dynamic visual capture in the depth plane compared to binocular and eye-patched viewing control participants. Similar to both binocular and eye-patched viewing controls, people with one eye perceived the direction of the auditory signal to be moving in the direction of the incongruent visual signal despite being asked to respond to the auditory signal alone. The current results are consistent with previous research on healthy controls that observed a robust dynamic capture effect, where the perceived direction of motion of the auditory signal was influenced by an ignored visual stimulus moving in the opposite direction (Harrison, 2012; Jian et al., 2008; Kitajima & Yamashita, 1999). In addition, people with one eye showed no difference in reaction time or accuracy compared to monocular and binocular viewing controls for any of the conditions (unimodal visual looming and receding, unimodal auditory looming and receding, congruent looming and receding and incongruent looming and receding). Furthermore, people with one eye show similar magnitude of dynamic visual capture compared to binocular and eye-patched viewing controls indicating that there is no difference between groups in how the visual stimulus influences the perception of the auditory stimulus.

As in previous studies, a greater degree of visual capture is observed for incongruent audiovisual motion in depth conditions where the visual cue captures an auditory cue moving in the opposite direction (Harrison, 2012). In the current study, visual capture tends to be larger (although not significantly so) when the visual stimulus is looming compared to receding. This suggests that looming visual cues are more highly perceptually weighted during multisensory integration compared to receding visual cues (Alais & Burr, 2004; Ernst and Banks, 2002). This increased weighting for looming visual stimuli confers an ecological advantage since an approaching object could make contact with the observer in an adverse way. The increased weighting of the visual cue may be the result of increased attention directed towards the looming visual stimulus which leads to increased interference during auditory direction detection (Harrison, 2012). In a study investigating audiovisual integration of looming stimuli Cappe and colleagues (2009) demonstrated that participants selectively integrate congruent audiovisual looming stimuli resulting in behavioural facilitation (in the form of quicker reaction times) and enhancement of the impression of movement (Cappe et al., 2009). These results indicate a preference for congruent looming stimuli that result in behavioural facilitation possibly due to the ecological advantage of early detection of an approaching object. These findings support our current results where increased dynamic visual capture is observed when a looming visual stimulus is paired with a receding auditory stimulus. Since visual information is typically considered fast and reliable when making perceptual judgments increased weighting of the looming visual cue may result in similar behavioural and movement perception facilitation. Surprisingly, people with one eye do not differ from binocular and patched viewing controls on this task given that people with one eye exhibit various audiovisual processing differences. These differences include a lack of visual dominance for streams of auditory and visual stimuli compared to binocular and patched viewing controls (Moro & Steeves, 2012; 2013). Based on these findings it would be reasonable to predict that visual capture would be reduced in people with one eye, however this is not the case.

Attention contributes to and interacts with the way in which people view bimodal stimuli (Alais, Newell and Mamassian, 2010; Harris and Jenkin, 2001 for a review). While this task was not designed to explicitly modulate attention, it is possible that people with one eye have a more veridical perception of unimodal sensory inputs and that this is driven by attention. Based on previous findings indicating a lack of visual dominance in this group (Moro & Steeves, 2012; 2013), we would expect people with one eye to show less dynamic visual capture. However, in the current study it appears that people with one eye direct attention towards the visual modality, providing a greater opportunity to gather as much reliable information about the approaching or receding stimulus as possible, which could provide safety in the life-threatening situation of an approaching object. The current results indicate the possibility that through subconscious directed attention, people with one eye might adapt their unimodal sensory perception to be as veridical as possible based on the task.

In binocular viewing participants, Harrison and colleagues (2015) demonstrated that response accuracy during an audiovisual dynamic capture study was mediated by visual motion direction (increased dynamic visual capture for incongruent trials), as well as, stereo disparity (where a larger congruency effect was observed for 3D relative to 2D stimuli). Furthermore, through ERPs, they demonstrated that retinal disparity affects early processing (135-160ms) where 3D presentations show an enhanced congruency effect (difference between incongruent and congruent conditions) compared to 2D presentations (Harrison et al., 2015). People with one eye lack the ability to estimate depth using binocular cues in their environment, since removing an eye eliminates the use of binocular information to determine motion in depth through retinal disparity (Steeves et al., 2000).

There are, however, a large number of monocular cues to depth that are both static (e.g. occlusion and texture gradients) and dynamic (e.g. motion parallax) that people with one eye have the ability to use (Steeves et al., 2000; see Howard, 2002 for a review). Children who have had one eye removed have better depth discrimination for monocular depth cues through the increased use of head movements as they age compared to binocular viewing controls (González, Steinbach, Ono & Wolf, 1989). It has been observed, however, that people who have had one eye removed early in life poorly estimate time to collision of a looming stimulus when only monocular cues to depth are available (Steeves et al., 2000). In the current study, it is likely that attention is directed towards the visual modality in order to counteract the inaccurate estimation of time to collision observed in people with one eye (Steeves et al., 2000). Increased attentional load devoted to using monocular cues to depth may contribute to making the best estimation of time to collision. Directing attention towards the auditory modality, as in previous audiovisual tasks (Moro & Steeves, 2012; 2013; Moro, Harris & Steeves, 2014), would be maladaptive in this case since the auditory stimulus was sometimes incongruent with the visual stimulus. This modulation of attention is ecologically important for survival. Since people with one eye have a 50% reduction of the visual input to their brain, it is possible that they direct their attention towards vision to attempt to gather the most information possible from the remaining sensory input and allow them to better understand the complex stimuli being presented to them. It is possible that people who have had one eye removed make use of as many processing mechanisms as possible to partially compensate for the lack of binocular information.

In conclusion, people with one eye appear to demonstrate the same susceptibility for dynamic visual capture as binocular and eye patched viewing controls. This consistent behaviour may be the result of directing attention towards the visual modality, their deficient sense, in order to gain important information about approaching and receding stimuli despite being asked to respond to the auditory signal alone. Directing attention towards their deficient sense is atypical in this patient group and may be the result of an adaptation for their loss of visual input to provide an ecological advantage to distinguish potentially adverse approaching stimuli. This is unlike previous audiovisual studies with this group where stimuli did not convey an ecological threat (Moro & Steeves, 2012; 2013). Future studies investigating dynamic capture using more ecologically valid every day objects that produce sounds which could be perceived as both threatening and not threatening, as well as, studies manipulating attention towards a specific modality will help address emerging questions relating to this patient group. The current results contribute to the likelihood that accommodations are present for audiovisual processing that are unique to people with one eye since they do not show consistent processing preferences for audiovisual stimuli. It appears that sensory processing is modulated for each unique sensory situation in this patient group. These accommodations may serve as an adaptive compensatory mechanism for the loss of half of the visual input to the brain.

Acknowledgements

We sincerely thank all of our participants for their participation in this study. This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada NSERC), as well as the Canada Foundation for Innovation to JKES. SSM is supported by NSERC, Toronto Rehabilitation's TD Graduate Scholarship for People with Disabilities and York University.

CHAPTER IV

AUDIOVISUAL PLASTICITY FOLLOWING EARLY ABNORMAL VISUAL EXPERIENCE: REDUCED MCGURK EFFECT IN PEOPLE WITH ONE EYE[3]

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[3] Moro, S. S. & Steeves, J. K. E. (2018). *Neuroscience Letters*, DOI: 10.1016/j.neulet.2018.02.031.

Abstract

Previously, we have shown that people who have had one eye surgically removed early in life during visual development have enhanced sound localization (Hoover et al., 2012) and lack visual dominance, commonly observed in binocular and monocular (eye-patched) viewing controls (Moro & Steeves, 2012). Despite these changes, people with one eye integrate auditory and visual components of multisensory events optimally (Moro et al., 2014). The current study investigates how people with one eye perceive the McGurk effect, an audiovisual illusion where a new syllable is perceived when visual lip movements do not match the corresponding sound (McGurk & MacDonald, 1976). We compared individuals with one eye to binocular and monocular viewing controls and found that they have a significantly smaller McGurk effect compared to binocular controls. Additionally, monocular controls tended to perceive the McGurk effect less often than binocular controls suggesting a small transient modulation of the McGurk effect. These results suggest altered weighting of the auditory and visual modalities with both short and long-term monocular viewing. These results indicate the presence of permanent adaptive perceptual accommodations in people who have lost one eye early in life that may serve to mitigate the loss of binocularity during early brain development.

A unique model for examining the consequences of the loss of binocularity on the development of the visual system is early unilateral eye enucleation, the surgical removal of one eye (see Steeves, Gonzalez & Steinbach, 2008, for a review). Unlike other forms of early monocular visual deprivation such as congenital cataract, strabismus, ptosis or anisometropia that leave abnormal visual input during visual development, removing the eye completely eliminates all visual input from that eye to the developing brain (Steeves et al., 2008).

Losing one eye early in life, during postnatal visual system maturation, leads to altered use of auditory and visual sensory information in individuals who are tested later in life, as mature adults. This altered use of auditory and visual sensory information is a consequence of the 50% reduction in visual input to the brain compared to binocularly intact individuals. Similar to people who are congenitally blind (e.g., Lessard et al., 1998), people with one eye are more accurate at sound localization in all locations compared to control participants who were monocular viewing (eye-patched), binocular viewing or with their eyes closed (Hoover et al., 2012). In addition, participants with one eye do not show the typical tendency to mislocate sounds towards the 'straight ahead' as do controls (Hoover et al., 2012).

People with one eye do not show the typical pattern of visual dominance, commonly observed in binocularly intact individuals, known as the Colavita visual dominance effect (Colavita, 1974; Egeth & Sager, 1977; Colavita & Weisberg, 1979; Sinnett et al., 2008; Spence, 2009; Spence, Parise & Chen, 2011). Specifically, when asked to categorize rapidly presented audiovisual targets consisting of line drawings and common sounds, people with one eye process the auditory and visual stimuli equally, while controls favour vision (Moro

& Steeves, 2012). This suggests that people with one eye have a preferential adaptation of the auditory component of audiovisual stimuli and this contributes to balancing out and eliminating the typical dominance of vision over audition (Moro & Steeves, 2012).

Integrating vision and hearing is an important aspect of how we process our rich sensory environment. When presented with paired auditory and visual stimuli that appear to originate from the same spatial location at the same time, a single fused perceptual event is often perceived (Welch & Warren, 1980). When the components of an audiovisual stimulus are displaced relative to one another in space, individuals typically perceive a single event that is spatially displaced towards the visual component. This is known as the ventriloquism effect (Welch & Warren, 1980; Bertelson & Aschersleben, 1998; Alais et al., 2010; Alais & Burr, 2004). The ventriloquism effect paradigm is often used as a model for examining audiovisual integration. People with one eye localize audiovisual stimuli similarly to control groups viewing binocularly or monocularly (Moro et al., 2014). However, they take longer to localize unimodal visual compared to unimodal auditory stimuli unlike binocular and monocular viewing controls (Moro et al., 2014). Together, these data suggest that people with one eye have advantageously altered their ability to process multisensory information and that visual information may have a longer processing time, likely as an adaptation for their loss of visual input.

The McGurk effect is an audiovisual illusion where a new syllable is perceived when visual lip movements do not match the corresponding auditory sound (McGurk & MacDonald, 1976). The McGurk illusion has become a popular tool for studying the mechanisms underlying multisensory integration, despite demonstrating inter-subject variability (Alsius, Paré & Munhall, 2017; Basu Mallick, Magnotti & Beauchamp, 2015).

Recently it has been shown that people with amblyopia have a reduced McGurk effect that persists with both eyes viewing (Narinesingh et al., 2014). This indicates that the underlying causes are associated with more complex sensory processes that are not specific to visual acuity (Narinesingh et al., 2014) and are likely cortical in nature. Quantifying the McGurk effect in people who have had one eye removed early in life can contribute to understanding the development of audiovisual processing.

The current study investigates how people with one eye perceive the McGurk effect compared to binocular and monocular (eye-patched) viewing controls. The monocular viewing control group serves to address whether findings are simply associated with a transient 50% reduction in visual input. Given the previously described audiovisual processing differences in people with one eye (Moro & Steeves, 2012; Moro & Steeves, 2013; Moro, Harris & Steeves, 2014), we predict that there will be a reduced McGurk effect in participants with one eye compared to binocular and monocular viewing controls. This is plausible given the decreased McGurk effect observed in patients with amblyopia (Narinesingh et al., 2014). Furthermore, it is possible that there will be a reduction in the illusory McGurk percept as a result of the lack of visual dominance in people with one eye (Moro & Steeves, 2012).

Materials and Methods

Participants

People with One Eye (Monocular Enucleation, ME):

Eight adult participants who had undergone monocular enucleation (ME) at The Hospital For Sick Children participated in this study (mean age = 34 years, SD = 13). All ME participants had been unilaterally eye enucleated (6 right eye removed) due to retinoblastoma, a rare childhood cancer of the retina. Age at enucleation ranged from 4 to 66 months (mean age at enucleation = 24 months, SD = 19).

Binocular Viewing Control Participants (BV):

Twenty binocularly intact controls with a mean age of 27 years (SD = 9) were tested viewing stimuli out of both eyes.

Monocular Viewing Control Participants (MV):

Twenty binocularly intact participants, with a mean age of 27 years (SD = 10), completed the experiments with one eye patched. Participants' non-preferred eye (determined using the Porta test) was patched with a semi-opaque eye covering and translucent tape (10 right-eye covered).

All participants from each group (ME, BV, MV) reported normal hearing (self-report) and normal or corrected-to-normal acuity as assessed by an EDTRS eye chart (Precision Vision™, La Salle, IL) and wore optical correction if needed. Control participants completed the experiment in either the binocular or monocular viewing control group. All participants gave informed consent prior to their inclusion in the study, which was approved by York University's Office of Research Ethics.

Stimuli

Visual stimuli consisted of two 2-second videos of a female speaker mouthing the syllables "ba" or "ga," with each presentation containing the entire articulation of the syllable similar to those used by Quinto and colleagues (2010). Auditory stimuli consisted of two 2-second audio clips of the female speaker from the videos saying the syllables "ba" or "ga." Audiovisual stimuli consisted of two 2-second videos of the female speaker saying the syllables "ba" or "ga," paired with the corresponding video, respectively. McGurk illusory stimuli consisted of video footage of the female speaker mouthing the "ga" syllable but paired with the auditory sound clip of the female speaker saying "ba" (Figure 4.1). Stimuli were presented using SuperLab stimulus presentation software (Cedrus Inc).

Procedure

Participants sat at a distance of 60 cm from a 21.5" computer screen in a dimly lit testing room. Auditory stimuli were presented to the participants using *Sony Studio Monitor Series* noise cancelling headphones placed over their ears with the volume regulated to a comfortable hearing level by the participants. All participants were instructed to respond as quickly as possible to unimodal visual, unimodal auditory or bimodal stimuli. Participants were instructed to indicate using a RB-530 response pad (Cedrus Inc) whether they perceived the woman in the video to say "ba," "ga" or "da" by indicating their response on one of the three corresponding designated keys. Participants were given verbal instructions and a short practice session for familiarization with the task.

Participants viewed 20 repetitions per condition with a 500 ms interstimulus interval consisting of silence and a blank screen for a total of 140 trials.

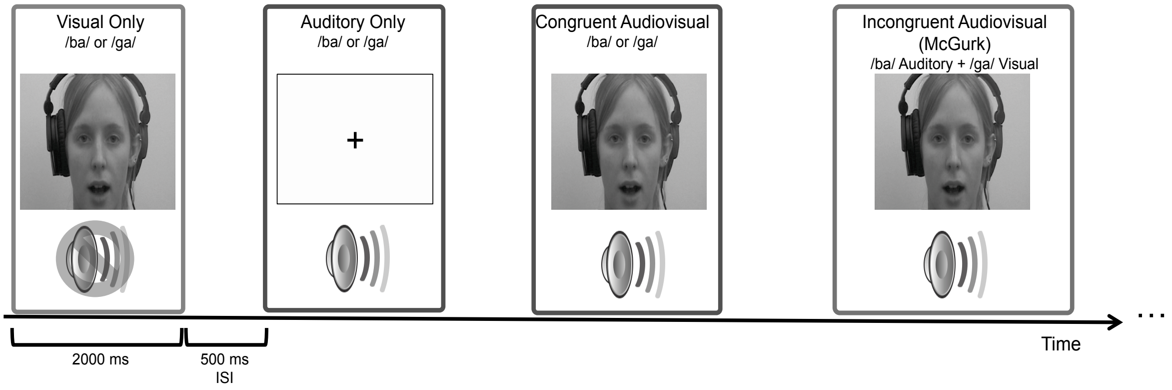

Figure 4.1. A schematic illustration of the presentation of stimuli. Visual only stimuli, presented to participants in colour, consisted of 2-second videos of a female speaker mouthing the syllables "ba" or "ga." Auditory only stimuli consisted of 2-second audio clips of the female speaker from the videos saying the syllables "ba" or "ga." Congruent audiovisual stimuli consisted of 2-second videos of the female speaker saying the syllables "ba" or "ga," paired with the corresponding video of the congruent mouth articulations. Incongruent audiovisual (McGurk) stimuli consisted of video footage of the female speaker mouthing the "ga" syllable but paired with the auditory sound clip of the female speaker saying "ba."

Results

Reaction time

A 4 × 3 repeated measures analysis of variance (ANOVA), calculated using Type II sum of squares, comparing reaction time for group (ME vs. BV vs. MV) and condition (auditory only, visual only, audiovisual, McGurk) was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(5) = 24.130$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.775$) was used. There was no significant interaction, $F(6, 135) = 0.752$, $p = 0.578$, $\eta_p^2 = 0.032$ or main effect of participant group, $F(2, 45) = 0.909$, $p = 0.410$, $\eta_p^2 = 0.039$. There was a main effect of condition, $F(3, 135) = 25.814$, $p < 0.001$, $\eta_p^2 = 0.365$. Bonferroni corrected post hoc comparisons revealed that the audiovisual reaction time was faster compared to visual, auditory, and McGurk reaction times ($p < 0.001$). Additionally, the auditory reaction time was faster than the McGurk reaction time ($p = 0.002$). There was no difference in reaction time between the ME, MV, and BV groups. Figure 4.2 plots the reaction time for each for the BV, MV and ME groups.

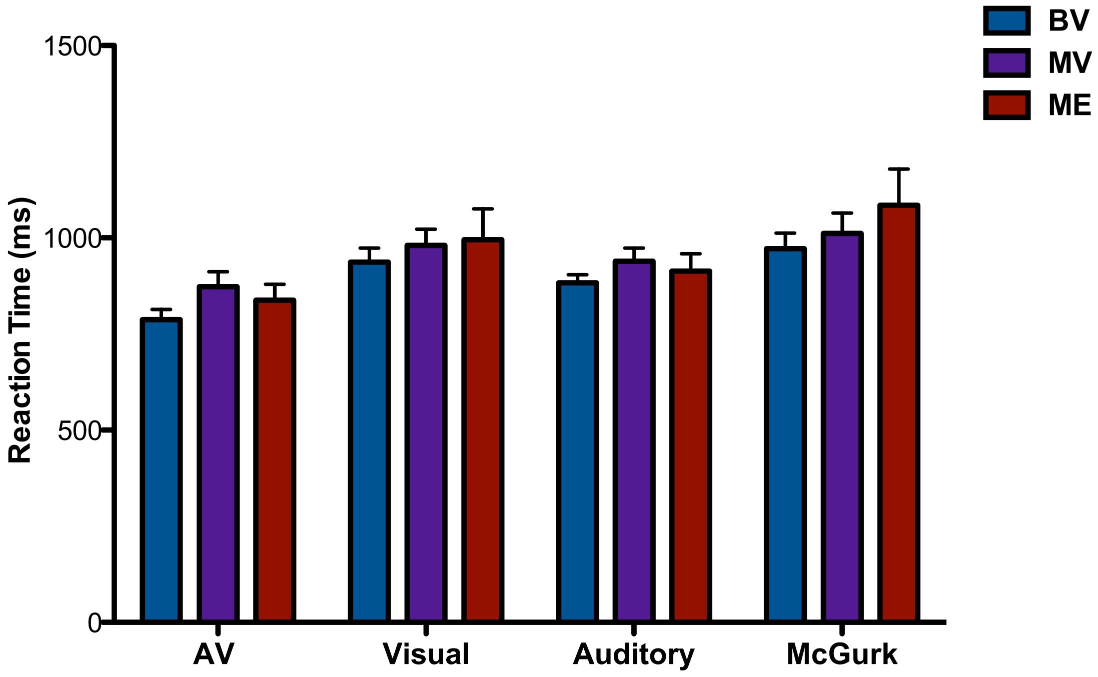

Figure 4.2. Reaction times (ms) for each condition: audiovisual (AV), visual only, auditory only and McGurk for each group, binocular viewing (BV, blue), monocular viewing (MV, purple) and monocular enucleation (ME, red).

Non-McGurk stimulus accuracy

A 6 × 3 repeated measures analysis of variance (ANOVA) comparing accuracy for participant group (ME vs. BV vs. MV) and condition (auditory “ba” and “ga”, visual “ba” and “ga”, audiovisual “ba” and “ga”) was conducted. Mauchly’s test indicated that the assumption of sphericity was violated ($\chi^2(14) = 113.596$, $p < 0.001$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.582$) was used. There was a significant interaction, $F(10, 225) = 2.183$, $p = 0.050$, $\eta_p^2 = 0.088$ and main effect of condition, $F(2, 225) = 33.502$, $p < 0.001$, $\eta_p^2 = 0.427$. There was no significant main effect of participant group, $F(2, 45) = 2.881$, $p = 0.067$, $\eta_p^2 = 0.113$. Bonferroni corrected post hoc comparisons revealed that participants were less accurate at detecting visual only stimuli compared to audiovisual ($p < 0.001$) and auditory stimuli ($p = 0.002$). There was no difference in accuracy between the ME, MV and BV groups. Figure 4.3 plots the accuracy of the non-McGurk trial stimuli for the BV, MV and ME groups.

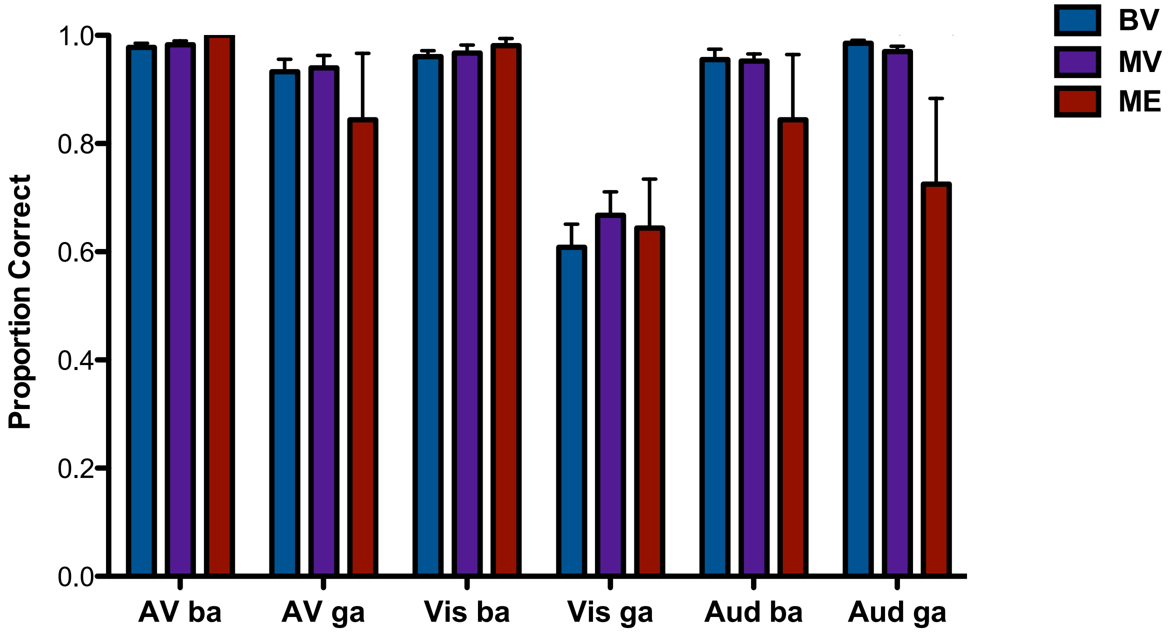

Figure 4.3. Accuracy (proportion correct) for each non-McGurk trial type: audiovisual (AV), visual only (Vis), auditory only (Aud) for each group, binocular viewing (BV, blue), monocular viewing (MV, purple) and monocular enucleation (ME, red).

McGurk effect

A 3 × 3 repeated measures analysis of variance (ANOVA) comparing group (ME vs. BV vs. MV) and syllable ("ba" vs. "ga" vs. "da") was conducted. Mauchly's test indicated that the assumption of sphericity was violated ($\chi^2(2) = 11.334$, $p = 0.003$), therefore a Greenhouse-Geisser correction ($\varepsilon = 0.815$) was used. There was a significant interaction, $F(4, 90) = 3.186$, $p = 0.025$, $\eta_p^2 = 0.124$, main effect of syllable, $F(2, 90) = 5.582$, $p = 0.009$, $\eta_p^2 = 0.110$ and main effect of participant group, $F(2, 45) = 3.152$, $p = 0.050$, $\eta_p^2 = 0.123$. Bonferroni corrected post hoc tests were conducted comparing across groups. The BV group perceived the illusory "da" syllable (McGurk illusion) more often than the ME group ($p = 0.012$). There was a trend for the BV group to also perceive the illusory "da" more often than the MV group ($p = 0.076$). The ME group perceived the visual component "ga" more often during the McGurk trials compared to the BV group ($p = 0.050$). Bonferroni corrected post hoc tests were conducted comparing across syllable condition. The BV group perceived the illusory "da" more often than the auditory component "ba" ($p = 0.008$) and the visual component "ga" ($p < 0.001$). The MV group perceived the illusory "da" more often than the auditory component "ba" ($p = 0.069$) and the visual component "ga" ($p = 0.013$). The ME group did not show a significant difference in the perception of the illusory "da," or auditory "ba" and visual "ga" syllables. Figure 4.4 plots the proportion of each syllable perceived during the McGurk condition for the BV, MV and ME groups.

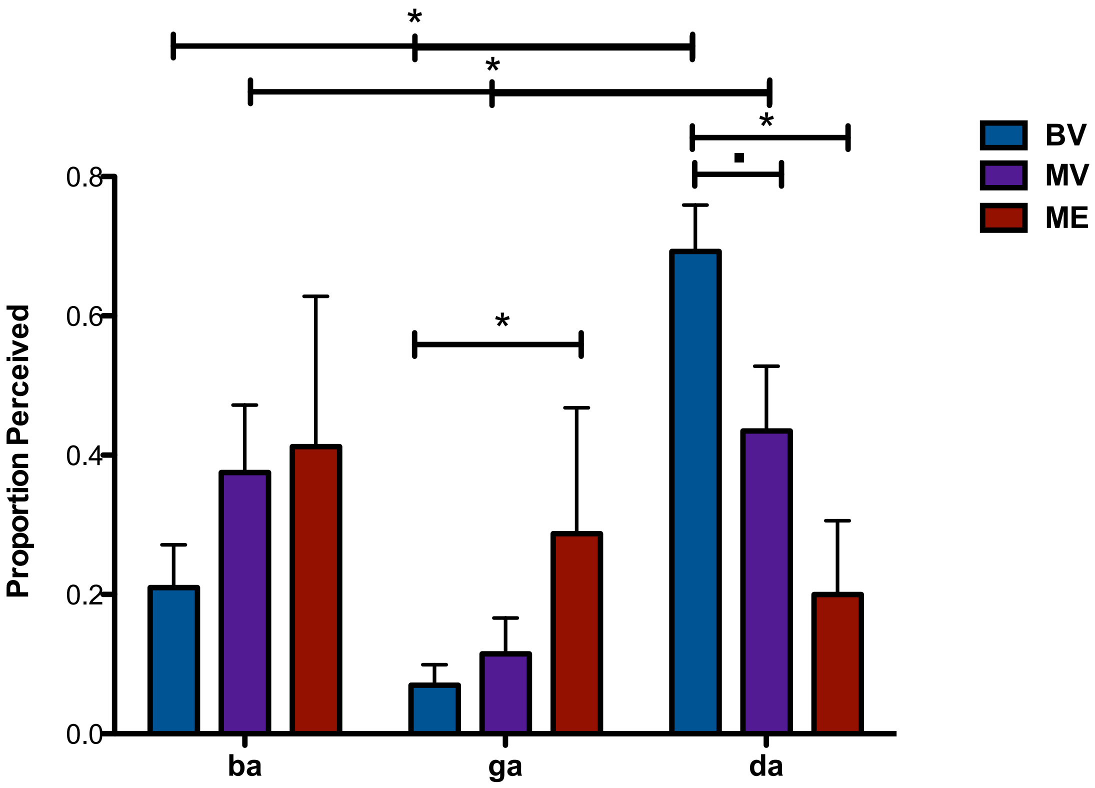

Figure 4.4. Proportion of each syllable perceived during the McGurk condition for the BV (blue), MV (purple) and ME groups (red). The "ba" syllable represents the auditory component, the "ga" syllable represents the visual component and the "da" syllable represents the illusory McGurk perception. (* $p < 0.05$; **.** $p < 0.08$).

Discussion

The current study investigated how people with one eye perceive the McGurk effect compared to binocular and monocular viewing controls. People with one eye perceived the illusory McGurk effect less often than binocular viewing controls. They did not differ from either control group in terms of accuracy for unimodal visual, unimodal auditory and congruent audiovisual stimuli. Further, they showed no difference in reaction time compared to binocular or monocular viewing controls for any of the conditions. Finally, the monocular viewing controls tended to perceive the illusory McGurk syllable less often than binocular viewing controls indicating a transient modulation of the McGurk effect with eye patching. This is the first time that we document a modulation of audiovisual processing in controls with eye patching. Overall, these results show a more veridical perception of unimodal sensory inputs during audiovisual events and less susceptibility to the audiovisual illusion with long-term visual deprivation in people with one eye and a small effect in controls with short-term visual deprivation from eye patching. This may occur as adaptation of integration mechanisms for auditory and visual signals due to the reduction of visual input from one eye both short-term from eye patching and long term from eye enucleation during early postnatal visual maturation.

The present findings are consistent with previous research indicating a number of audiovisual processing differences in people with one eye compared to binocularly intact individuals. Differences demonstrated in previous studies include a lack of the typical pattern of visual dominance (Colavita visual dominance effect) for audiovisual events despite no difference in reaction times (Moro & Steeves, 2012) and slower reaction times to low level audiovisual stimuli despite normal audiovisual spatial integration (Moro, Harris & Steeves, 2014). The current study shows a reduction in the perception of the McGurk effect and no difference in reaction time for people with one eye compared to binocular and monocular viewing controls consistent with previous research using high-level stimuli (Moro & Steeves, 2012). It is possible that plasticity during postnatal development alters the ability of people with one eye to process low-level sensory information resulting in slower visual processing time in order to achieve normal audiovisual integration performance. It could be that such an adaptation for low level audiovisual stimuli in turn leads to a reduction in the perception of audiovisual illusions for more complex high-level stimuli and thereby more veridical perception of unimodal sensory inputs for multisensory events. The current results involving complex higher-level stimuli (faces and voices) are consistent with previous findings for higher-level stimuli in this group (Moro & Steeves, 2012). It has recently been shown that the visual and auditory system white matter tracts are altered in people with one eye and could account for longer processing times in this patient group (Wong et al., 2017). This altered wiring could increase signal transmission to higher-level cortical regions in the visual and auditory systems thereby resulting in the slower reaction times observed in previous studies (Moro, Harris & Steeves, 2014).

While the McGurk effect is likely driven by perceptual processes, it can also be modulated by attention (Navarra et al., 2010; Alsius, Paré & Munhall, 2017). It is likely that top-down modulation from attention, which is known to contribute to and interact with perception, plays a role in the way in which people perceive bimodal stimuli (see Murray et al., 2016, for a review). Low-level stimulus factors work concurrently with higher-level processes including attentional allocation (Murray et al., 2016). Given the reduction of 50%

of the visual input to their brain, it is possible that people with one eye direct (re-weight) attention towards low-level physical characteristics of stimuli (Murray et al., 2016) and subsequently this affects processing of unimodal sensory inputs. Such audiovisual adaptation following early postnatal visual deprivation would affect the way in which complex multisensory events are processed and the maturation of underlying brain mechanisms. This may contribute to a reduction in the perception of audiovisual illusions (Moro & Steeves, 2012; 2013). At first glance, our current results appear in conflict with the previous findings of a lack of visual dominance (increased weighting of the auditory modality) in this group (Moro & Steeves, 2012; 2013) since they perceive the visual ("ga") syllable more often than binocular viewing controls during the McGurk task. However, in general, people with one eye do not preferentially perceive either of the unimodal syllables (auditory "ba" or unimodal visual "ga") when compared to the illusory ("da") syllable. This is unlike controls who perceive the illusory ("da") syllable most often. This indicates that people with one eye do not completely redirect attention towards just one sense over the other but rather they direct attention towards both senses equally, still suggesting reweighting. Monocular viewing controls demonstrated intermediate susceptibility to the McGurk effect compared to binocular viewing controls and people with one eye indicating that short-term visual deprivation at the time of testing appears to modify attentional processes. Furthermore, the monocular viewing control group were similar to the people with one eye since they did not have a preference for perceiving the illusory "da" syllable more often compared to the unimodal auditory "ba" component. This modification may be due to the transient reduction of vision from one eye and the physical addition of the eye patch onto their face that could be accounted for by increased attention directed towards the auditory modality. Since the monocular viewing control group was intermediate in their perception of the McGurk illusion compared to the binocular viewing control group and people with one eye, it is unlikely that the same adaptive mechanisms present in people with one eye are activated while viewing audiovisual stimuli. This is the first time that our group has found a trend for an effect of monocular viewing in controls on audiovisual perception. Future research directly investigating the influence of attention in people with one eye and monocular viewing controls, as well as, testing the same participants in both control groups and comparing the change in performance would contribute useful evidence to this emerging question.

It is also possible that susceptibility to the McGurk effect is dependent on inter-individual differences in the cognitive processes intervening at the binding stage (Alsius, Paré & Munhall, 2017). A reduced susceptibility to the illusion has been found in a number of clinical conditions including autism (e.g. Stevenson et al., 2014; Bebko et al., 2013), schizophrenia (e.g. deGelder et al., 2003), learning disabilities (Boliek et al., 2010), and amblyopia (Narinesingh et al., 2014; see Alsius, Paré & Munhall, 2017, for a review). Alsius and colleagues (2017) suggest that individual differences disrupting the McGurk illusion could be due to: (1) superior sensitivity in detecting audiovisual correspondences, where the auditory and visual sensory signals would not erroneously be attributed as belonging to the same event; (2) higher/lower weighting of the unimodal sensory cues, where the higher weighted modality will more greatly contribute to the perception of the event; (3) poor integration of the sensory cues, where poorer integration will contribute to the perception of individual auditory and visual events that are not fused into a single event or perhaps a combination of these. Given that people with one eye have optimal audiovisual spatial integration in accordance with the Maximum Likelihood Estimate (MLE) (Moro, Harris & Steeves, 2014), poor integration of the sensory cues is not a reasonable explanation for the differences observed in this group. Our current results, in conjunction with previous findings from this patient group, instead support the notion that altered sensory weighting, perhaps modulated through attentional processes, contributes to the group differences that disrupt the illusion. Future studies should investigate whether people with one eye are more sensitive to audiovisual correspondences to specifically address whether this explanation could work in conjunction with altered unimodal stimulus weighting.

In conclusion, people with one eye appear to have an altered ability to process sensory information, likely as an adaptation for their loss of visual input. They show less susceptibility to the McGurk effect compared to binocular viewing controls. These results contribute to the growing body of work indicating postnatal plasticity leading to accommodations in audiovisual processing in people with one eye. Finally, we suspect that the group differences in this task are accounted for by altered weightings of the sensory inputs for multisensory events. These accommodations likely serve as an adaptive compensatory mechanism for the loss of half of the visual input to the brain.

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CHAPTER V

SHORT AND LONG-TERM VISUAL DEPRIVATION LEADS TO ADAPTED USE OF AUDIOVISUAL INFORMATION FOR FACE-VOICE RECOGNITION[4]

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[4] Moro, S. S., Hoover, A. E. N. & Steeves, J. K. E. (2018). *Vision Research*. DOI: 10.1016/j.visres.2018.01.009.

Abstract

Person identification is essential for everyday social interactions. We quickly identify people from cues such as a person's face or the sound of their voice. A change in sensory input, such as losing one's vision, can alter how one uses sensory information. We asked how people with only one eye, who have had reduced visual input during postnatal maturation of the visual system, use faces and voices for person identity recognition. We used an old/new paradigm to investigate unimodal (visual or auditory) and bimodal (audiovisual) identity recognition of people (face, voice and face-voice) and a control category, objects (car, horn and car-horn). Participants learned the identity of 10 pairs of faces and voices (Experiment 1) and 10 cars and horns (Experiment 2) and were asked to identify the learned face/voice or car/horn among 20 distractors. People with one eye were more sensitive to voice identification compared to controls viewing binocularly or with an eye-patch. However, both people with one eye and eye-patched viewing controls use combined audiovisual information for person identification more equally than binocular viewing controls, who favour vision. People with one eye were no different from controls at object identification. The observed visual dominance is larger for person compared to object identification, indicating that faces (vision) play a larger role in person identification and that person identity processing is unique from that for objects. People with long-term visual deprivation from the loss of one eye may have adaptive strategies, such as placing less reliance on vision to achieve intact performance, particularly for face processing.

We typically experience a combination of different sensory stimuli at the same time each day. Social interaction is often an important part of one's day ranging from chatting with friends to identifying whether an approaching individual is a friend or foe. Multisensory cues, such as seeing a person's face and hearing their voice provide important information that contribute to distinguishing an individual person's identity. If all of our sensory systems are intact, we use them to our full advantage.

Humans with complete visual deprivation have shown evidence for changes in other sensory systems that indicate enhanced abilities with their remaining senses following a complete loss of a sensory system. For instance, congenitally blind individuals have shorter response times for auditory discrimination tasks (Röder et al., 1999), faster processing of language (Röder et al., 2002), enhanced sound localization (Lessard, Paré, Lepore & Lassonde, 1998) and enhanced tactile perception (Sathian, 2000) compared to sighted individuals. This suggests underlying physiological changes within the systems responsible for these senses to support these behavioural enhancements. If visual input were reduced by half, as in people with one functioning eye, it seems reasonable to expect that the other intact sensory systems should function to the best of their ability in order to adapt and compensate for the partial loss of vision.

Monocular blindness, resulting from the surgical removal of one eye (enucleation) represents a unique human model for examining the consequences of the loss of binocularity. It is unlike other more common forms of monocular deprivation such as amblyopia or strabismus since the removal of the end organ eliminates all forms of visual input to the brain from that eye (Kelly, Moro & Steeves, 2012). People with one eye have enhanced sound processing ability compared to controls (Hoover, Harris & Steeves, 2012).

When presented with auditory stimuli along the horizontal azimuth, people with one eye have consistently more accurate spatial localization within a field of +/- 78 degrees compared to control participants who were monocular viewing, binocular viewing or with their eyes closed (Hoover, Harris & Steeves, 2012).

Typically, when we are simultaneously presented with auditory and visual stimuli, the visual information is processed preferentially over auditory information. This is also known as the Colavita visual dominance effect (Colavita, 1974). People with one eye do not demonstrate the Colavita effect when asked to categorize rapidly presented audiovisual targets consisting of line drawings of common objects paired with common sounds (Moro & Steeves, 2012). Instead, people with one eye process auditory and visual components of audiovisual targets equally. Together with the enhanced auditory spatial localization (Hoover, Harris & Steeves, 2012), these results suggest that auditory information may be processed more reliably for people with one eye and could be a form of sensory compensation for the loss of binocularity.

A common illusion occurs when the auditory and visual components of an audiovisual stimulus are spatially displaced relative to one another, resulting in the perception of a single event typically displaced towards the visual component, known as the ventriloquism effect (Welch & Warren, 1980). People with one eye show similar audiovisual localization for spatially disparate audiovisual stimuli compared to controls viewing binocularly or with one eye-patched (Moro, Harris & Steeves, 2014). However, unlike binocular and eye-patched controls, people with one eye take longer to localize unimodal visual stimuli compared to unimodal auditory stimuli (Moro, Harris & Steeves, 2014).

For the most part, spatial visual ability is intact or somewhat better than controls in people who have lost one eye early in life, despite a 50% reduction of visual input to the visual brain. For example, the ability to discriminate low-contrast global shape, a more complex visual process (hyperacuity), is enhanced in people with one eye compared to eye-patched controls and controls viewing dichoptically (Steeves et al., 2004). Face processing, however, has emerged as an exception. People with one eye do not show the composite face effect and they take longer to process the shape and spacing between internal facial features (Kelly, Gallie & Steeves, 2012). This mild impairment is face-specific and was not replicated when performing the same tasks on stimuli from other visual image categories, namely houses (Kelly, Gallie & Steeves, 2012).

Face perception is a unique and multi-faceted aspect of vision (Leopold & Rhodes, 2010). The ability to identify a person is facilitated when face information is integrated with voice information through crosstalk between the unimodal visual and unimodal auditory percepts (Campanella & Belin, 2008). Previous exposure to combined face-voice information during person identity encoding facilitates identification of that individual when only unimodal cues (face or voice) are available (Ellis, Jones & Mosdell, 1997; Schweinberger, Herholz & Sommer, 1997; Sheffert & Olson, 2004; von Kriegstein et al., 2008). Bimodal identity recognition shows interference effects (increased reaction time and decreased accuracy) due to the addition of auditory information to visual information when identifying bimodal (face-voice) stimuli (Joassin, Maurage, Bruyer, Crommelinck & Campanella, 2004). This suggests that because unimodal face recognition is superior to voice recognition, the addition of voice information interferes with the efficient processing of the face (during bimodal face-voice pairings). When face stimuli are degraded and therefore less reliable relative to the voices, bimodal stimulus presentations led to an enhancement effect indicating that the more reliable sensory information (face or voice) has greater influence on person identity recognition (Joassin, Maurage & Campanella, 2008).

Face-voice integration effects, similar to those found in healthy controls (Campanella & Belin, 2008), are seen in infants as young as 4 months of age (Bahrick, Netto & Hernandez-Reif, 1998) and in non-human primates (Izumi & Kojima, 2004). This suggests that face-voice identification improves with development and experience as older infants (7 months of age) have better face-voice matching compared to younger infants (4 months of age) (Bahrick, Netto & Hernandez-Reif, 1998). People who have had one eye removed early in life experience monocular deprivation during postnatal visual system maturation. The long-term consequences of this abnormal visual experience during development may result in altered use of auditory and visual sensory information when tested later in life, as mature adults.

The current study investigates how people with one eye use auditory and visual information for person and object identity recognition compared to binocular and eye-patched viewing controls. Since people with one eye have half of the visual input to the brain, will this alter face-voice integration? Will audiovisual integration be affected more generally and also alter the identification of audiovisual objects (cars paired with horns)? Using the same paradigm as Hoover, Démonet and Steeves (2010) we measure visual, auditory and audiovisual recognition of people and objects in people with one eye compared to eye-patched and binocular viewing controls. The addition of an eye-patched control group compares whether the effects observed in people with one eye are simply due to monocular viewing or whether they are the result of long-term visual deprivation from eye enucleation. In Experiment 1, we quantify person recognition for faces, voices and face-voice pair combinations. We predict that people with one eye will have poorer person identification compared to controls as a result of reduced sensitivity to faces since previously we have shown mild face perception impairments in this monocular group (Kelly, Gallie & Steeves, 2012). In Experiment 2, we quantify object recognition for cars, car horns and car-car horn pair combinations. We predict no difference in object identification between groups. We have previously shown that higher-level aspects of spatial form vision are intact (Kelly, Gallie & Steeves, 2012) or somewhat enhanced (Steeves et al., 2004) for this group compared to binocular and eye-patched viewing controls. We also compare across experiments to assess whether person recognition is unique compared to object recognition.

Experiment 1: Person identity recognition

Materials and Methods

Participants

People with One Eye (Monocular Enucleation, ME):

Eleven adult participants who had undergone early monocular eye enucleation (ME) at The Hospital For Sick Children (Toronto) participated in this study (mean age = 34 years, SD = 12). All ME participants had been unilaterally eye enucleated (7 right eye removed) due to retinoblastoma, a rare childhood cancer of the retina. Age at enucleation ranged from 4 to 66 months of age (mean age at enucleation = 22 months, SD = 16).

Binocular Viewing Control Participants (BV):

Twenty-five binocularly intact controls with a mean age of 27 years (SD = 7) were tested while viewing stimuli binocularly.

Patched Viewing Control Participants (MV):

Twenty-five binocularly intact participants, with a mean age of 24 years (SD = 3), completed the experiments with one eye patched. Participants' non-preferred eye (determined using the Porta test) was patched with a semi-opaque eye covering and translucent tape (12 right-eye covered).

All participants (ME, BV, MV) reported normal hearing and normal or corrected-to-normal acuity as assessed by an EDTRS eye chart (Precision Vision™, La Salle, IL) and wore optical correction if needed. All participants gave informed consent prior to their inclusion in the study, which was approved by York University Office of Research Ethics.

Stimuli

Stimuli were previously used in Hoover et al. (2010) for assessing face and object identities in a patient with visual agnosia. See Hoover et al. (2010) for more detailed information on how stimuli were created. In short, visual stimuli consisted of 110 greyscale female face images that were cropped within an oval aperture and distinguishable features such as beauty marks removed. Auditory stimuli were 20s in duration and were played through headphones. Each consisted of a short neutral passage spoken in English by one of 110 female voices.

Participants sat 45cm from the display in a dimly lit room with the head stabilized by a chin/forehead rest. All stimuli were presented with Superlab 4.0 (Cedrus, Inc) and participants indicated their responses using designated keys on a keyboard.

Procedure

The current experimental procedure follows that used by Hoover et al. (2010).

Learning phase: Participants learned the identities of 10 individuals who were previously unknown. Each "identity" consisted of a visual face image paired with a voice stimulus. Participants were told that they would be tested on their ability to recognize these 10 identities and that they had to learn to associate each specific face with its corresponding voice. Participants viewed a static face image and listened to its paired voice for 20s. A fixation-cross (500ms in duration) appeared before the visual stimuli (Figure 5.1A). Each of the ten identities was presented four times. In total, the learning phase lasted approximately 15 minutes.

Pre-test phase: Following the learning phase participants were given a short pre-test to ensure an adequate level of learning of the paired face/voice identities. During this phase participants heard one of the learned voices and saw two of the learned faces displayed side by side, one of which corresponded to the voice. Participants were instructed to press a button on the response pad corresponding to which of the two faces matched the voice that they heard. Participants were unable to advance to the next trial until they responded correctly. The same trial was repeated immediately after the incorrect trial until the correct response was given. Upon selection of a correct response the trial would end and proceed to the following one (Figure 5.1B). Each voice was initially presented twice to yield a minimum of 20 trials. In total, the pre-test phase lasted approximately 7 minutes.

Testing phase: This phase followed the pre-test phase and consisted of two different blocks (unimodal visual or auditory) and bimodal (face-voice pairs). During the unimodal block participants viewed a visual face image alone or heard a voice stimulus alone and were asked to identify as quickly and accurately as possible whether the identity of the stimulus was learned or new. The ten learned face or voice identities were presented twice among 20 new (unlearned) distractor faces and 20 new voices. The unimodal block consisted of 40 face only trials and 40 voice only trials for a total of 80 trials presented in random order. In the bimodal block, participants heard a voice and saw a face at the same time. Participants were asked to identify as quickly and accurately as possible whether the face-voice identity was learned or new using a designated button on a response pad. A correct learned identity consisted of a congruent presentation of a previously learned face and voice. 10 learned identities were presented twice each among 30 new distractor identities for a total of 50 trials presented in random order. The faces and voices were paired in four different combinations: (1) a learned face with a learned voice (congruent), (2) a learned face with a new voice (incongruent), (3) a new face with a learned voice (incongruent), (4) a new face with a new voice (congruent) (Figure 5.1C). In total, the testing phase lasted a maximum of approximately 40 minutes.

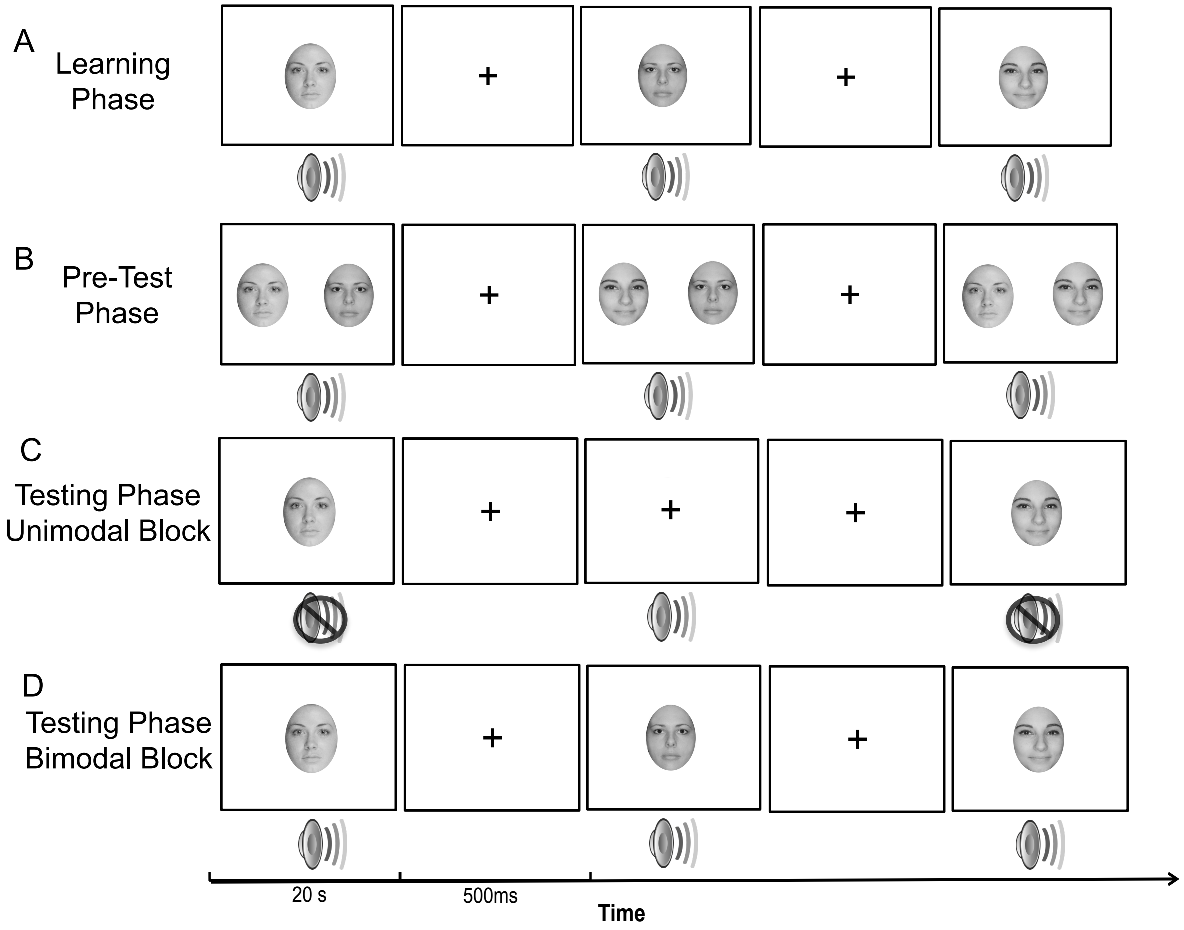

Figure 5.1. Schematic diagram representing the task in Experiment 1. A. Learning phase. B. Pre-test phase. C. Testing Phase Unimodal Block. D. Testing Phase Bimodal Block.

Results

Sensitivity (*d'*) scores were calculated for all conditions (visual only, auditory only, overall bimodal, congruent bimodal and incongruent bimodal) for all participants. The overall bimodal sensitivity scores were calculated based on both congruently and incongruently paired stimuli. Some participants had perfect performance, which was addressed by adjusting the values according to the method recommended by Macmillan and Creelman (1991) for perfect scores.

To evaluate bimodal enhancement (or interference), we calculated bimodal effect scores by subtracting the unimodal sensitivity score, either visual or auditory, from the congruent bimodal score. To evaluate the effect of a unimodal stimulus preference on bimodal performance, congruency effects with the bimodal pairings were investigated. We calculated a congruency difference score by subtracting the incongruent bimodal sensitivity (false alarms from the incongruent pairings were used in the calculation of the *d'* score) score from the congruent bimodal sensitivity score. In general the congruency effects allow us to evaluate the presence of a preference for unimodal stimuli (vision or audition) in overall bimodal identity formation. For example, if binocular viewing controls make their recognition judgments based on their dominant modality (vision) then we would predict that they would respond that a learned face image paired with a new voice is a "learned" identity.

Overall identity recognition performance

A 3 × 3 repeated measures analysis of variance (ANOVA) was conducted to compare sensitivity scores for overall identity recognition performance in each participant group (ME vs. BV vs. MV) and stimulus condition (auditory only, visual only, overall bimodal).

There was a significant interaction, $F(4, 116) = 5.228$, $p = 0.001$, $\eta_p^2 = 0.153$ and main effect of condition, $F(2, 116) = 49.019$, $p < 0.001$, $\eta_p^2 = 0.458$. There was a trending main effect of participant group, $F(2, 58) = 3.055$, $p = 0.055$, $\eta_p^2 = 0.095$. Bonferroni corrected post-hoc tests for the main effect of condition indicated a significant heightened sensitivity to voice only stimuli compared to the BV group for the MV group ($p = 0.003$) and ME group ($p = 0.008$). Bonferroni corrected post-hoc tests were conducted for the interaction comparing the sensitivity scores in each modality for each participant group. The sensitivity scores for the BV group visual (face only) was greater compared to both auditory (voice only) ($p< 0.001$) and bimodal (face/voice) ($p< 0.001$). Additionally the bimodal (face/voice) was greater compared to the auditory (voice only) ($p< 0.001$). The sensitivity scores for the MV group visual (face only) was greater compared to the auditory (voice only) ($p< 0.001$) but not bimodal (face/voice) ($p = 0.150$). Additionally the bimodal (face/voice) was greater compared to the auditory (voice only) ($p= 0.004$). The sensitivity scores for the ME group visual (face only) was greater compared to the auditory (voice only) ($p= 0.029$) but not compared to bimodal (face/voice) ($p= 1.000$). Additionally there was no difference in bimodal (face/voice) compared to the auditory (voice only) ($p= 0.270$). Figure 5.2 plots the sensitivity scores for each for the BV, MV and ME groups for unimodal auditory, unimodal visual and bimodal conditions.

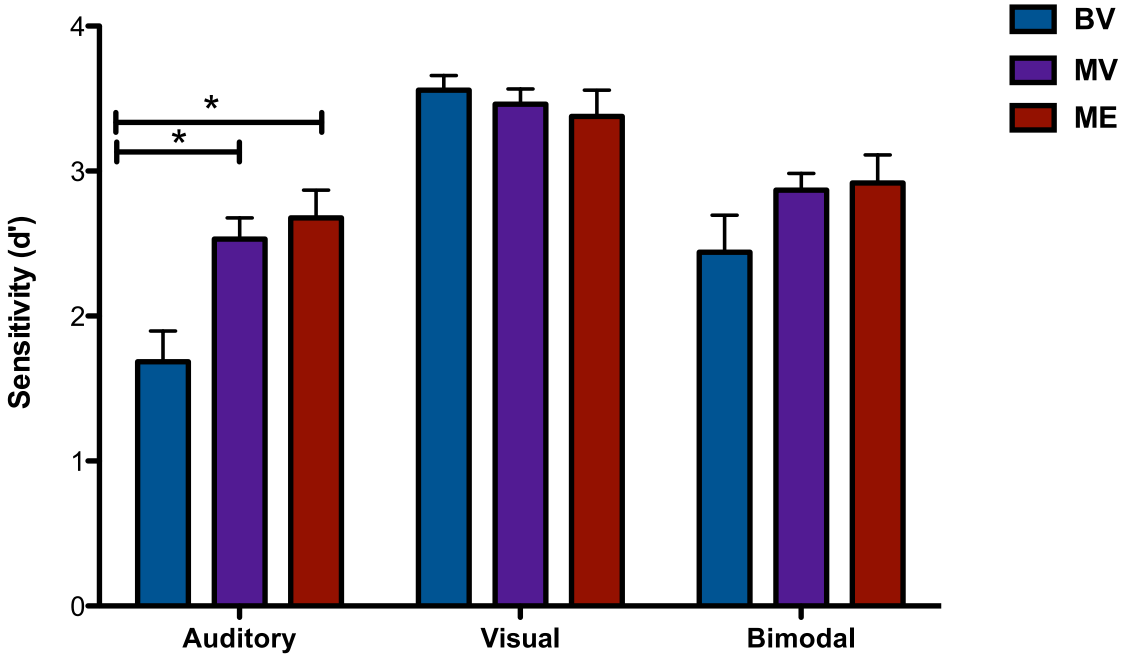

Figure 5.2. The sensitivity scores (d') for overall identity recognition for each of the BV (blue), MV (purple) and ME groups (red) for the unimodal auditory, unimodal visual and bimodal conditions. Significant differences in sensitivity are indicated by * ($p < 0.05$).

Bimodal effect scores

Visual effect score: A one way ANOVA comparing sensitivity to unimodal visual stimuli compared to bimodal stimuli (congruent bimodal sensitivity – voice only sensitivity) in each participant group (ME vs. BV vs. MV) was not significant, $F(2, 60) = 2.114$, $p = 0.130$. The ME, MV and BV groups did not differ in sensitivity when faces and voices were paired together compared to when voices were tested alone. One sample t-tests were conducted to determine whether the bimodal effect scores for each participant group indicated a significant enhancement effect (significantly different from zero). A significant enhancement effect was found for the BV (t (24)=3.523, $p = 0.025$) and the MV group (t (24)=2.443, $p = 0.022$). No significant enhancement was found for the ME group (t (10)=1.669, $p = 0.126$). Figure 5.3 plots the difference in sensitivity (d') of the visual effect scores for each for the BV, MV and ME groups.

Auditory effect score: A one way ANOVA comparing the effect of sensitivity to unimodal auditory stimuli compared to bimodal stimuli (congruent bimodal sensitivity – face only sensitivity) in each participant group (ME vs. BV vs. MV) was significant, $F(2, 60) = 3.665$, $p = 0.032$. Bonferroni corrected post-hoc tests indicate that the BV group demonstrated increased interference compared to the MV group ($p = 0.05$) when faces and voices were paired together compared to when faces were tested alone. One sample t-tests were conducted to determine whether the bimodal effect scores from each participant group indicated a significant interference effect (significantly different from zero). A significant interference effect was found for all participant groups, BV (t (24)=-4.640, $p < 0.001$), MV (t (24)=-4.689, $p < 0.001$) and ME groups (t (10)=-2.894, $p = 0.016$). Figure 5.3

plots the difference in sensitivity (d’) of the auditory effect scores for each of the BV, MV and ME groups.

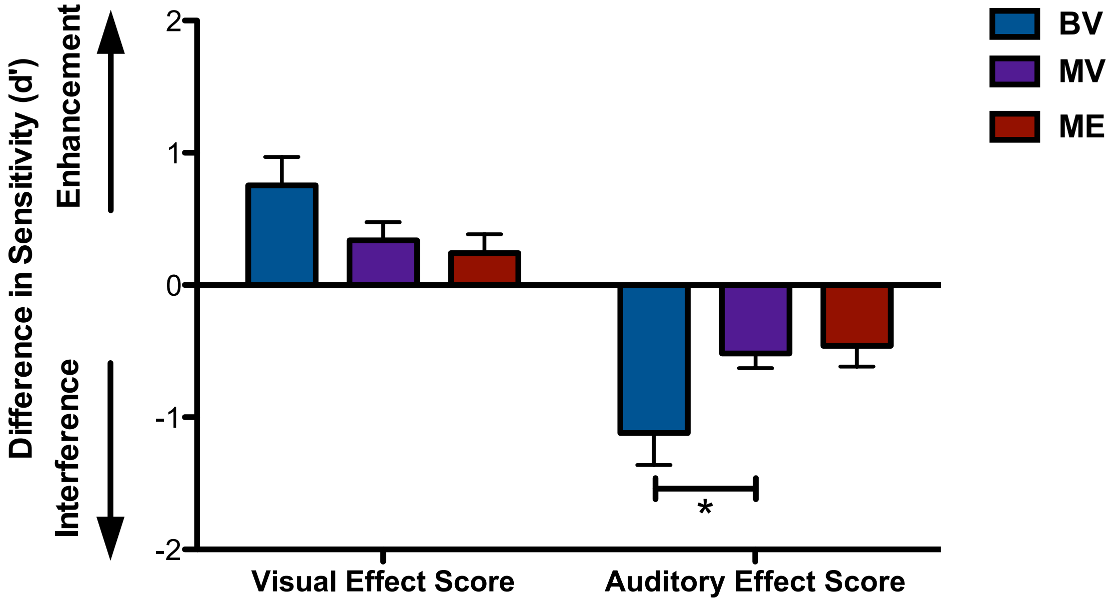

Figure 5.3. Visual effect scores: congruent bimodal-unimodal auditory (first three columns) and the auditory effect scores: congruent bimodal-unimodal visual (last three columns) for each of the BV (blue), MV (purple) and ME (red) groups. Significant differences are indicated by * ($p < 0.05$).

Congruency difference scores

A one way ANOVA comparing sensitivity to congruency (congruent bimodal sensitivity – incongruent bimodal sensitivity) in each participant group (ME vs. BV vs. MV) was significant, $F(2, 60) = 6.873$, $p = 0.002$. Bonferroni corrected post-hoc tests indicated that the BV group had higher sensitivity compared to the MV group ($p = 0.014$) and ME group ($p = 0.006$) when learned faces and voices were paired together congruently compared to an incongruent pairing (a learned face or voice paired with a new voice or face). One sample t-tests were conducted to determine whether each participant group demonstrated a preference for congruently paired bimodal stimuli (significantly greater congruency difference compared to zero). A significant preference for congruently paired bimodal stimuli was found for the BV group, ($t\,(24)=4.168$, $p < 0.001$). No significant differences were found for the MV ($t\,(24)=0.794$, $p=0.435$) and ME groups ($t\,(10)=-0.908$, $p = 0.385$). Figure 5.4 plots the congruency difference scores for each of the BV, MV and ME groups.

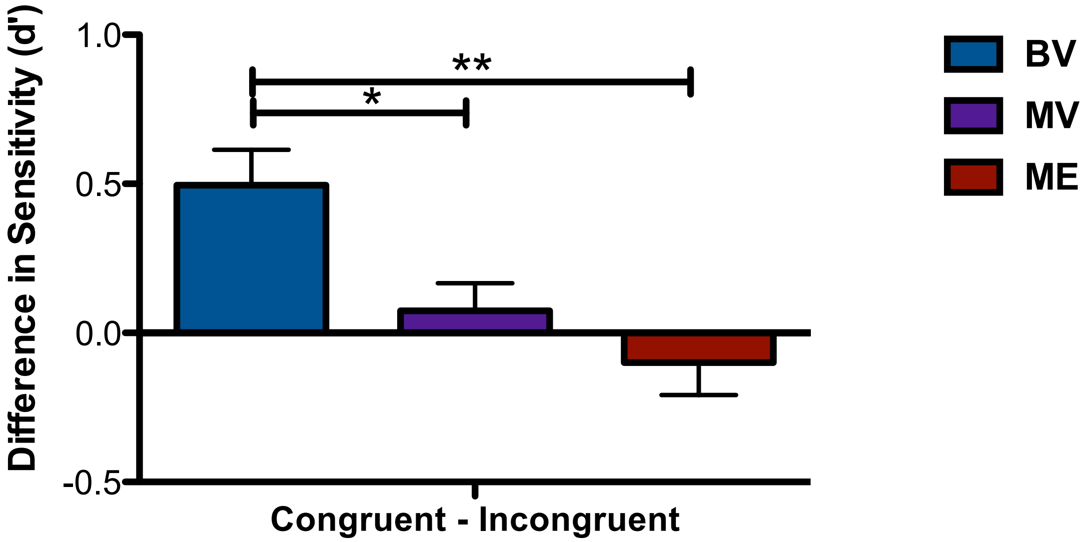

Figure 5.4. Difference in sensitivity (d') for the congruency difference scores plotted for each of the BV (blue), MV (purple) and ME (red) groups. Significant differences are indicated by * ($p < 0.05$) and ** ($p < 0.001$).

Summary of person identity recognition results

In Experiment 1, people with one eye and eye-patched controls were more sensitive to unimodal voice stimuli compared to binocular viewing participants (Figure 5.2, auditory sensitivity). This suggests an adaptation to the reduction of visual input from one eye in general. All three participant groups demonstrated a significant interference effect when their bimodal sensitivity score was compared to their unimodal visual sensitivity score (Figure 5.3, auditory effect score). Binocular viewing controls showed significantly greater interference in their auditory effect score compared to eye-patched viewing controls and moreover showed greater (but not significant) interference compared to people with one eye (Figure 5.3, auditory effect score). This indicates that the additional information from the voice hindered identification for the binocular viewing controls. People with one eye and eye-patched controls showed greater sensitivity to voices compared to the binocular controls and the addition of the voice information to a visual face did not change sensitivity as much as it did for binocular viewing controls who had poor voice sensitivity.

People with one eye did not show a difference in performance compared to binocular and eye-patched viewing controls when their bimodal sensitivity score was compared to their unimodal auditory sensitivity score (Figure 5.3, visual effect score). Furthermore, people with one eye did not show a significant enhancement in bimodal sensitivity, unlike both control groups. This indicates that, despite not demonstrating an enhancement effect, the additional information from their partially deprived sense did not hinder their performance as they did not differ from either control group.

Binocular viewing controls demonstrated a preference for congruently paired bimodal stimuli while both eye-patched controls and people with one eye were not affected to the same extent by the incongruently paired bimodal stimuli (Figure 5.4). This suggests that binocular viewing controls likely made their recognition judgments based on their dominant sensory modality (vision) more often than eye-patched controls and people with one eye. This conclusion can be made by evaluating the data in conjunction with binocular viewing controls' increased enhancement of their visual effect score and increased interference in their auditory effect score.

Experiment 2: Object identity recognition

In Experiment 2, we sought to determine whether these audiovisual differences were specific to person identity or whether they occurred more generally for other audiovisual stimuli. We repeated these experiments with an object stimulus: cars and horns.

Materials and Methods

Participants

The same participants completed Experiment 1 and Experiment 2.

Stimuli

Stimuli consisted of 110 greyscale images of cars taken from the internet and resized (see Hoover et al., 2010). Auditory horn stimuli were 20s in duration and consisted of 110 different car horn sounds (see Hoover et al., 2010).

Procedure

As in Experiment 1, participants sat 45 cm from the display in a dimly lit room with the head stabilized by a chin/forehead rest. The procedure was identical to that for Experiment 1 throughout, substituting car images for faces and car horns for voices (Figure 5.5).

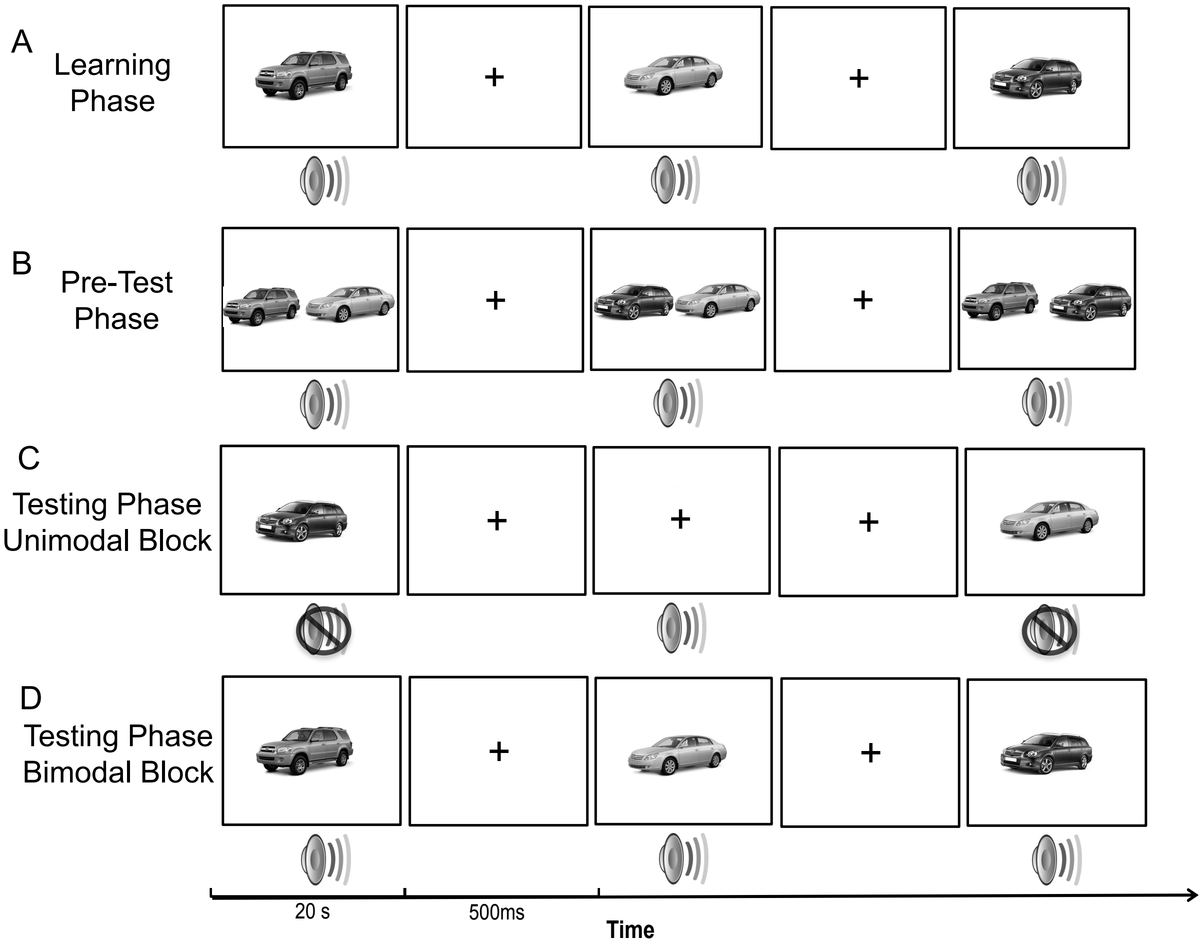

Figure 5.5. Schematic diagram representing the task in Experiment 2. A. Learning phase. B. Pre-test phase. C. Testing Phase Unimodal Block. D. Testing Phase Bimodal Block.

Results

The same analyses were used as in Experiment 1.

Overall identity recognition

A 3 × 3 repeated measures analysis of variance (ANOVA) comparing sensitivity scores for overall object identity recognition performance in each participant group (ME vs. BV vs. MV) and stimulus condition (auditory only, visual only, overall bimodal) revealed no significant interaction, $F(4, 116) = 1.501$, $p = 0.207$, $ŋ_{p}^{2} = 0.049$ or main effect of participant group, $F(2, 58) = 0.705$, $p = 0.498$, $ŋ_{p}^{2} = 0.024$. There was a main effect of condition, $F(2, 116) = 17.708$, $p < 0.001$, $ŋ_{p}^{2} = 0.234$. Bonferroni corrected post-hoc tests indicated that the participant groups were less sensitive to auditory stimuli (horns) compared to visual stimuli (cars) ($p = 0.005$) and bimodal (cars/horns) ($p = 0.048$). The ME, MV and BV groups did not demonstrate a difference in sensitivity across groups within any of the conditions. Figure 5.6 plots the sensitivity scores for each for the BV, MV and ME groups.

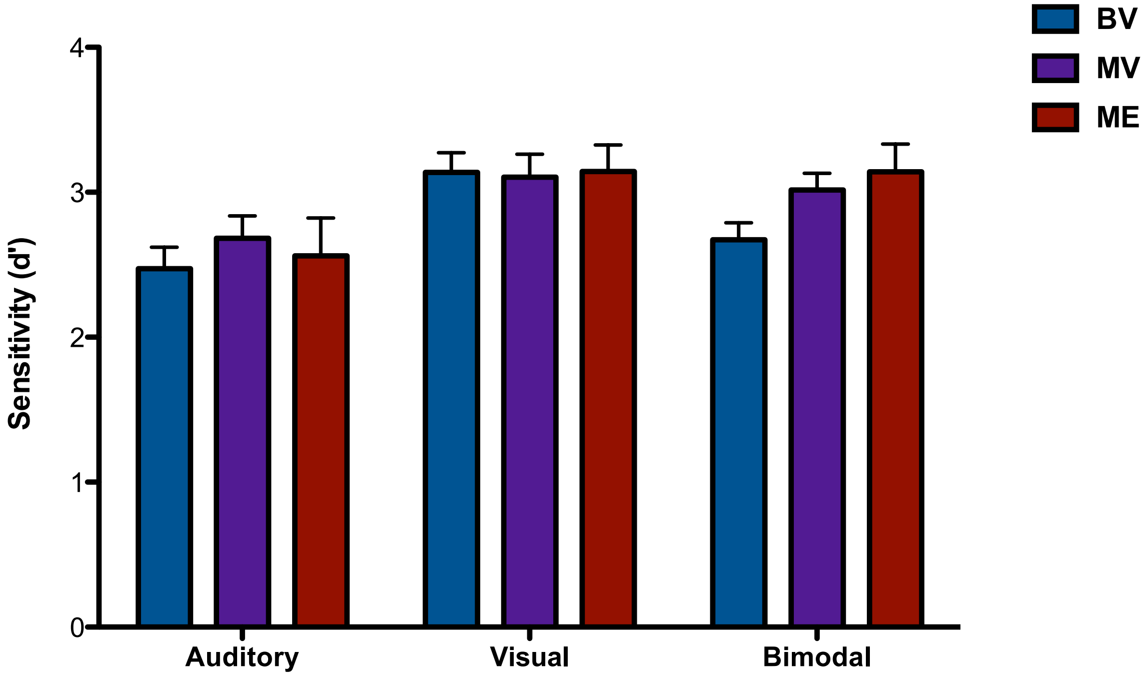

Figure 5.6. Sensitivity scores (d') for each of the BV (blue), MV (purple) and ME groups (red) for the unimodal auditory, unimodal visual and bimodal conditions.

Bimodal effect scores

Visual effect score: A one way ANOVA comparing sensitivity to unimodal visual stimuli compared to bimodal stimuli (congruent bimodal sensitivity – horn only sensitivity) in each participant group (ME vs. BV vs. MV) was not significant, $F(2, 60) = 1.266$, $p = 0.290$. The ME, MV and BV groups did not differ in sensitivity when cars and horns were paired together compared to when horns were tested alone. One sample t-tests were conducted to determine whether the bimodal effect scores from each participant group indicated a significant enhancement effect (significantly different from zero). A significant enhancement effect was found for the MV (t (24)=2.548, $p = 0.018$) and the ME group (t (10)=2.890, $p = 0.016$). No significant enhancement was found for the BV group (t (24)=1.482, $p = 0.151$). Figure 5.7 plots the difference in sensitivity (d') of the visual effect scores for each of the BV, MV and ME groups.

Auditory effect score: A one way ANOVA comparing sensitivity to unimodal auditory compared to bimodal sensitivity (congruent bimodal sensitivity – car only sensitivity) in each participant group (ME vs. BV vs. MV) was also not significant, $F(2, 60) = 2.770$, $p = 0.071$. The ME, MV and BV groups did not differ in sensitivity when cars and horns were paired together compared to when horns were tested alone. One sample t-tests were conducted to determine whether the bimodal effect scores from each participant group indicated a significant interference effect (significantly different from zero). A significant interference effect was found for the BV group (t (24)=-3.681, $p = 0.001$). No significant interference was found for the MV group (t (24)=-0.579, $p = 0.568$) or the ME group (t

(10)=-0.014, *p* = 0.989). Figure 5.7 plots the difference in sensitivity (d’) of the auditory effect scores for each of the BV, MV and ME groups.

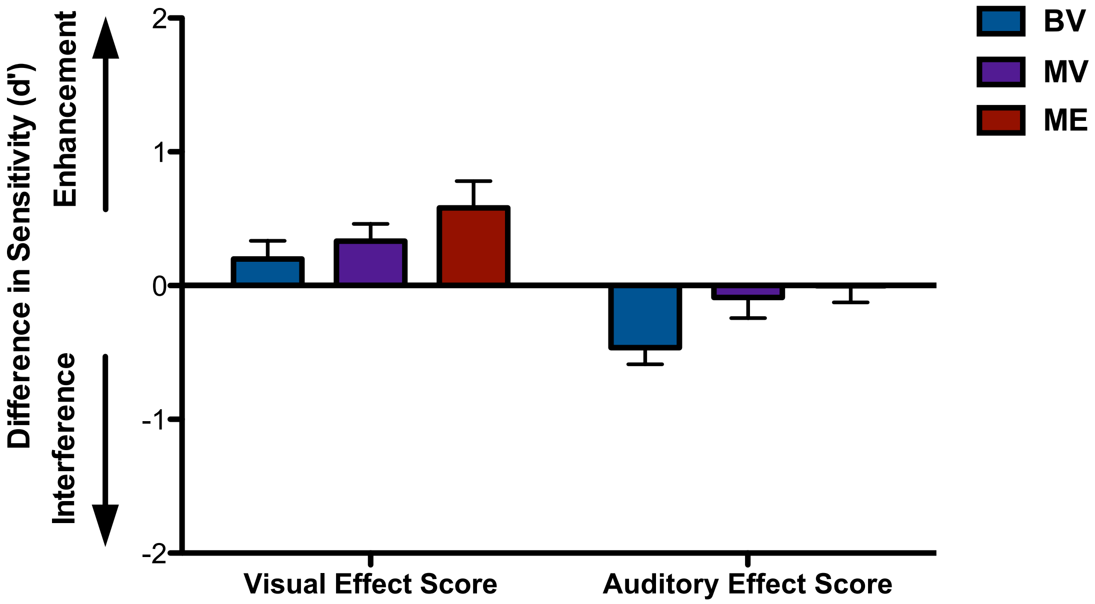

Figure 5.7. Visual effect scores: congruent bimodal-unimodal auditory (first three columns) and the auditory effect scores: congruent bimodal-unimodal visual (last three columns) for each of the BV (blue), MV (purple) and ME (red) groups.

Congruency differences

A one way ANOVA comparing sensitivity to congruency (congruent bimodal sensitivity – incongruent bimodal sensitivity) in each participant group (ME vs. BV vs. MV) was not significant, $F(2, 60) = 3.031$, $p = 0.056$. The BV group, MV group and ME group showed no difference in sensitivity when learned cars and horns were paired together congruently compared to an incongruent pairing made up of a learned car or horn and a new car or horn. One sample t-tests were conducted to determine whether each participant group demonstrated a preference for congruently paired bimodal stimuli (significantly greater congruency difference compared to zero). A significant preference for congruently paired bimodal stimuli was found for the BV group (t (24)=3.676, $p = 0.001$). No significant differences were found for the MV (t (24)=0.748, p =0.462) and ME groups (t (10)=-0.278, $p = 0.787$). Figure 5.8 plots the congruency difference scores for each of the BV, MV and ME groups.

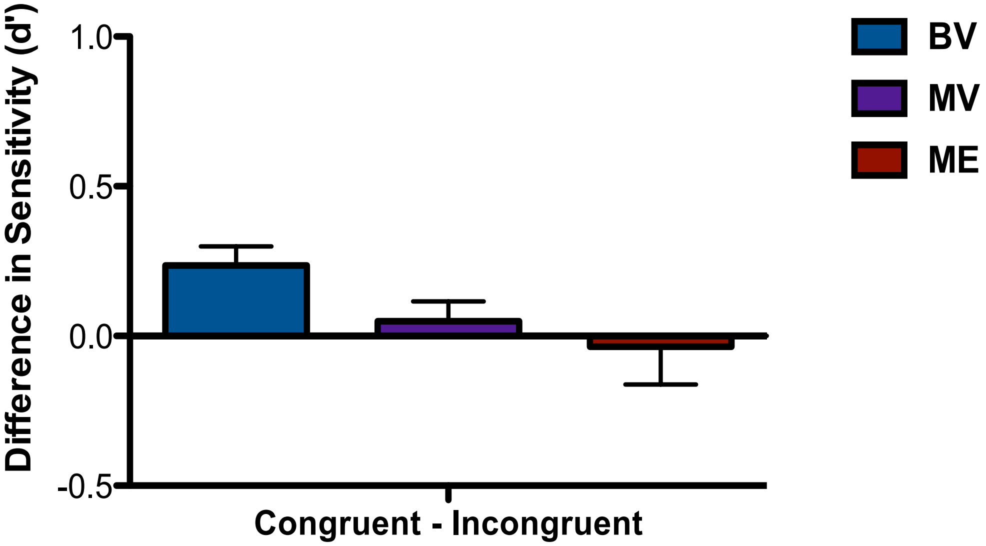

Figure 5.8. Difference in sensitivity (d') for the congruency difference scores plotted for each of the BV (blue), MV (purple) and ME (red) groups.

Summary of object identity recognition results

In Experiment 2, there was no difference in performance between groups for unimodal visual (car), unimodal auditory (horn) and bimodal (car-horn) stimuli sensitivity (Figure 5.6). This indicates that the auditory advantage demonstrated by people with one eye for auditory only stimuli is specific to person identification and does not generalize to object identification. The eye-patched control group and people with one eye demonstrated a significant enhancement effect when their bimodal sensitivity score was compared to their unimodal auditory sensitivity score (Figure 5.7, visual effect score). The binocular viewing control group demonstrated a significant interference effect when their bimodal sensitivity score was compared to their unimodal visual sensitivity score (Figure 5.7, auditory effect score). Overall, when comparing between participant groups however, people with one eye have no increased or decreased interference or enhancement for either of their bimodal sensitivity scores (Figure 5.7). All three groups did not differ in identifying congruently paired compared to incongruently paired bimodal stimuli (Figure 5.8).

Comparison across face-voice and car-horn tasks

Visual effect score – Face-voice vs. Car-horn: Paired samples t-tests were conducted to compare the visual effect scores obtained in each task (face-voice and car-horn) for each participant group (ME, BV and MV). A significant difference in visual effect scores was found across tasks for the BV group, $t(24) = 2.093$, $p = 0.047$. No significant differences in visual effect scores were found across tasks for both the MV group, $t(24) = 0.027$, $p = 0.979$ and ME group, $t(10) = -1.326$, $p = 0.214$. Figure 5.9 plots the visual effect scores for each task for the BV, MV and ME groups.

Auditory effect score – Face-voice vs. Car-horn: Paired samples t-tests were conducted to compare the auditory effect scores obtained in each task (face-voice and car-horn) for each participant group (ME, BV and MV). A significant difference between auditory effect scores was found across tasks for all of the participant groups: BV group, $t(24) = -2.440$, $p = 0.022$, MV group, $t(24) = -2.193$, $p = 0.038$ and ME group, $t(10) = -2.249$, $p = 0.048$. Figure 5.9 plots the auditory effect scores for each task for the BV, MV and ME groups.

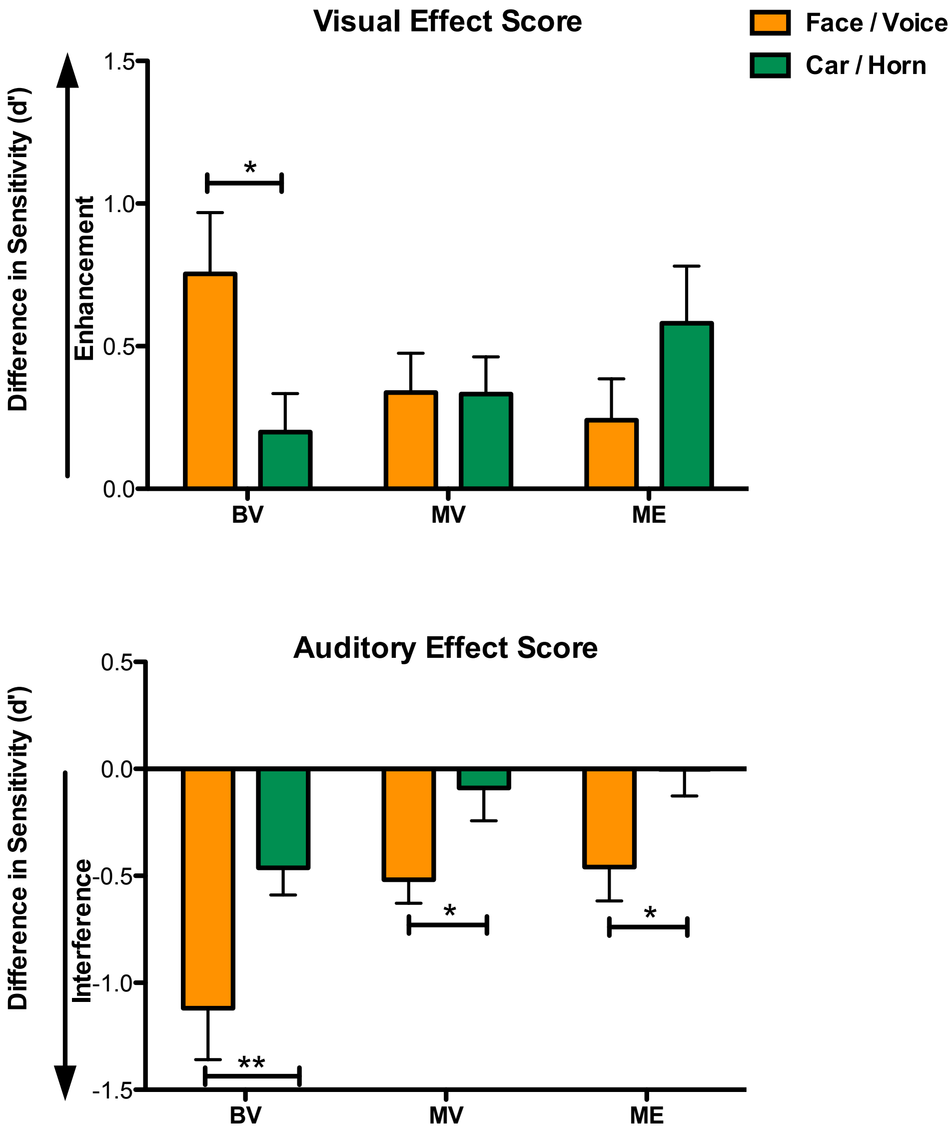

Figure 5.9. The visual effect score and auditory effect score for each task for each of the BV, MV and ME groups comparing across the face-voice (orange) and car-horn stimuli (green) tasks. Significant differences are indicated by * ($p < 0.05$).

Discussion

The current study investigated how people with one eye use auditory and visual information for person and object identity recognition compared to binocular viewing and eye-patched controls. When comparing across tasks, only the binocular viewing controls' sensitivity to person recognition was enhanced by adding the visual stimulus to the auditory stimulus (visual effect score) (Figure 5.9, BV group). This effect was limited to the person identity but not the object identity task. These results indicate a form of visual dominance for faces consistent with other visual dominance effects such as the Colavita effect (Moro & Steeves, 2012; 2013). Binocular viewing controls use visual information from faces to enhance person identification more than the visual information from cars to enhance object identification. Eye-patched viewing controls and people with one eye did not differ across tasks on their visual effect score suggesting a lack of visual dominance, consistent with previous research (Moro & Steeves, 2012). Additional information provided by the visual stimulus did not enhance bimodal sensitivity for either the eye-patched control group or people with one eye and had little effect on performance in the audiovisual condition for either person and object identity. This is likely due to a ceiling effect given the high sensitivity for the unimodal condition. All groups showed greater interference on their auditory effect score, where additional information provided by the auditory stimulus more greatly interfered with bimodal sensitivity in the face-voice task (Experiment 1). However, only the eye-patched viewing controls and people with one eye showed interference as per their auditory effect score for the car-horn task (Experiment 2). This result indicates that the additional auditory information from the voice hindered the sensitivity for person identification greater than the additional auditory information from the horns for object identification.

The binocular viewing controls have consistent performance with those from other face-voice person recognition studies (Hoover, Démonet & Steeves, 2010; Joassin, Maurage & Campanella, 2008). Unimodal face recognition is superior to voice recognition and the addition of voice information interferes with the efficient processing of the face during bimodal face-voice pairings in binocular viewing controls (Joassin, Maurage & Campanella, 2008). In the current study, people with one eye demonstrate increased sensitivity to faces compared to voices, similar to binocular viewing controls, however, they do not show increased sensitivity to faces compared to bimodal face-voice stimuli. People with one eye have mild impairments (are slower) in processing the shape and spacing between internal facial features indicating an overall subtle deficit in processing whole faces (Kelly, Gallie & Steeves, 2012). This deficit, although minor, might play a more substantial role in deciphering person identity and result in people with one eye taking greater advantage of available voice information for bimodal person identity recognition.

In the current study, the eye-patched viewing control group performs more similarly to the people with one eye rather than the binocular viewing control group. Our lab has previously found effects of monocular viewing from eye patching on low level, low contrast visual tasks (Reed et al., 1996; Steeves et al., 2004) and this is the first time that an effect of eye patching has been observed on higher level visual processing. The similar performance can be attributed to the overall reduction of visual input to the brain whether short-term from the eye-patch or long-term from early eye enucleation in childhood. Despite the reduction of visual input, bimodal person identification is nonetheless intact in both groups. These results support a top-down model of face and voice encoding where identification is modulated by supramodal brain regions rather than a bottom up model where extensive unisensory processing takes place to support supramodal brain regions (Maguiness & von Kriegstein, 2017; Latinus et al., 2010). Person identity performance may be affected by a reduction of visual input, however, it is important to note that the type of visual deprivation varies substantially between the two visually deprived groups in this study. On one hand, people with one eye likely undergo long-term developmental changes following early eye-enucleation that results in permanent cortical reorganization (Kelly et al., 2015; Moro et al., 2015) that contributes to altered underlying face-voice processing mechanisms. On the other hand, eye-patched viewing controls only experience short-term visual deprivation at the time of testing which appears to transiently alter the use or weighting of auditory information during face/voice recognition.

People with one eye have better sensitivity to voices compared to binocular controls. In accordance with the modality appropriateness hypothesis, the best sensory modality at processing a specific sensory dimension or stimulus attribute, should dominate (Welch & Warren, 1980). It is possible that the increased sensitivity in hearing voices allows for more use of voices for identity recognition and serves as an adaptive compensatory mechanism for the loss of one half of the visual input to the brain. The result is a more “balanced” contribution of each sense for bimodal (audiovisual) person identification and not a dominance of one sense (typically vision) over another.

The increased reliance on visual face information in all three participant groups (although greater for binocular viewing controls and eye-patched viewing controls) for person identification compared to object identification suggests that person identification is a unique process that is in some ways distinct from object identification. It has been shown that learned face-voice stimuli have underlying neural circuits that work in conjunction with one another (FFA, fusiform face area and TVA, temporal voice area) when comparing between sensory redundant stimuli (faces and voices) or arbitrary multimodal combinations (cell phones and ring tones) (von Kriegstein & Giraud, 2006). Information generated from person identification has stronger, more meaningful and ecological associations than those for object identification (Hoover, Démonet & Steeves, 2010). Visual face information, therefore, facilitates person identity recognition when presented in conjunction with a person's voice. People with one eye, despite demonstrating a difference between tasks, may still use audiovisual information equally for object identification and person identification, since they are better at voice recognition compared to binocular controls. In addition to demonstrating mild impairments in holistic face processing (Kelly, Gallie & Steeves, 2012), people with one eye lack typical visual dominance for non-face stimuli (Moro & Steeves, 2012), perhaps indicating more generalized decrease in visual dominance across higher level visual stimuli (such as both faces and objects). It has recently been shown that people with one eye have increases in surface area and gyrification in auditory and multisensory cortices in addition to the visual cortex (Kelly et al., 2015), as well as, a volume asymmetry in the MGB that may represent increased interactions between the left MGB and primary auditory cortex (Moro et al., 2015). These subcortical and cortical adaptations could support altered audiovisual contributions to person and object identification mechanisms.

In conclusion, short-term visual deprivation (from eye-patching) and long term visual deprivation (from removal of an eye early in life) decrease the reliability of face stimuli and may yield better use of voice information during face-voice person identification. People with one eye demonstrate evidence for a generalized altered audiovisual neural contributions to person identification that may serve as an adaptive compensatory mechanism for the loss of half of the visual input to the brain.

Acknowledgements

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CHAPTER VI

EVIDENCE OF MULTISENSORY PLASTICITY: ASYMMETRICAL MEDIAL GENICULATE BODY IN PEOPLE WITH ONE EYE[5]

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[5] Moro, S. S., Kelly, K. R., McKetton, L., Gallie, B. L. & Steeves, J. K. E. (2015). *NeuroImage: Clinical, 9,* 513-518.

Abstract

The medial geniculate body (MGB) plays a central role in auditory processing with both efferent and afferent tracts to primary auditory cortex. People who have lost one eye early in life have enhanced sound localization, lack visual over auditory dominance and integrate auditory and visual information optimally, similar to controls, despite taking longer to localize unimodal visual stimuli. Compared to controls, people with one eye have decreased lateral geniculate nuclei (LGN) volume as expected given the 50% deafferentation of the visual system. However, LGN volume is larger than predicted contralateral to the remaining eye, indicating altered structural development likely through recruitment of deafferented LGN cells. *Purpose:* the current study investigated whether structural MGB changes are also present in this group given the changes they exhibit in auditory processing. *Methods:* MGB volumes were measured in adults who had undergone early unilateral eye enucleation and were compared to binocularly intact controls. *Results:* unlike controls, people with one eye had a significant asymmetry with a larger left compared to right MGB, independent of eye of enucleation. MGB volume correlated positively with LGN volume in people with one eye. *Conclusions:* volume asymmetry in the MGB in people with one eye may represent increased interactions between the left MGB and primary auditory cortex. This interaction could contribute to increased auditory and other left hemisphere-dominant processing, including language, as compensation for the loss of one half of visual inputs early in life. The positive correlation between MGB and LGN volume is not due to space constraints but rather indicates increased plasticity in both auditory and visual sensory systems following early eye enucleation.

Every day, as we interact with the world, we take in important information from the environment through our sensory systems. Sensory information, with the exception of olfaction, is first processed subcortically by the thalamus, which then projects information to the cortex for further processing (Bartlett, 2013). There is evidence that when one sense is compromised, as in the case of complete blindness, brain regions associated with the lost sense (i.e., visual cortex) can be reorganized for use by the other senses (e.g., Röder et al., 2002). We have recently shown that structural reorganization at the subcortical level in the lateral geniculate nucleus (LGN) of the thalamus occurs in cases of sensory deprivation (Kelly et al., 2014).

The medial geniculate body (MGB) of the thalamus plays a central role in auditory processing (Devlin, 2006; Bartlett, 2013). It relays auditory information for higher order processing, however, substantial reciprocal connections from the primary auditory cortex back to the MGB also exist (Bartlett, 2013; Lee et al., 2004; Lee, 2012). This combination of ascending/descending sensory connections allows for the complex perception of sounds (Bartlett, 2013). In humans, functional magnetic resonance imaging (fMRI) has shown activation in the MGB during sound localization and sound recognition (Maeder et al., 2001), as well as, speech and emotional voice discrimination (von Kriegstein et al., 2008; Ethofer et al., 2012). Cortical feedback can alter MGB responses and provide dynamic gain enhancement or suppression through direct excitatory (corticothalamic feedback) or indirect inhibitory (corticothalamic influence on the thalamic reticular nucleus (TRN)) signals (Zhang et al., 1997; Bartlett, 2013). This gain control may contribute to enhancing auditory attention and context memory, important for predicting words in a spoken sentence (Bartlett, 2013).

Extensive investigation of the mammalian MGB, typically in the cat, has revealed three major subdivisions: ventral (vMGB), medial (mMGB) and dorsal (dMGB) (Devlin, 2006). The ventral division is sensitive to pure tone stimulation of the contralateral ear, whereas both the medial and dorsal divisions are more sensitive to complex and multisensory stimuli (see De Ribaupierre, 1997; Rouiller, 1997, for review). In addition, non-auditory stimuli also activate the MGB. The rat MGB responds to light flashes or rewards indicating that it plays a role in integrating multisensory stimuli to provide an enhanced contextual response (Komura et al., 2001, 2005; Bartlett, 2013). Congenitally deaf mice show reorganization at the level of the thalamus through the activation of the MGB (Hunt et al., 2005). Together, these findings indicate that it is possible for primary sensory afferents, such as retinal projections, to rewire and claim unused subcortical structures, resulting in anatomical re-modeling (Hunt et al., 2005; Karlen, 2006). Reorganization of the MGB following sensory loss, however, has not been studied extensively in humans.

Monocular enucleation, the surgical removal of one eye early in life, is a unique form of visual deprivation that provides a useful model for studying and quantifying the underlying neural consequences of the loss of binocularity during development. Monocular enucleation differs from other more common forms of monocular deprivation, such as strabismus and amblyopia, by providing a clean model of total monocular deprivation. This is unlike strabismus and amblyopia which result in unreliable, unbalanced competing visual signals from the deprived eye. Monocular enucleation results in only one stream of normal visual input from the remaining eye to the visual system. Monocular enucleation also provides an excellent model for investigating the interaction between vision and other senses, since vision has not been completely eliminated (see Kelly et al., 2013; Steeves et al., 2008, for reviews).

It has been well documented that the visual system changes in response to the loss of one eye. People who have had one eye removed early in life when the visual system is not yet mature demonstrate altered processing in their remaining senses. For example, they show intact (Cattaneo, 2014) or enhanced visual spatial form ability (Nicholas et al., 1996; Reed et al., 1997; Steeves et al., 2004), but reduced visual motion processing (see Steeves et al., 2008; Kelly et al., 2013, for reviews). Some evidence of cross-modal adaptation in response to the compromised enucleated visual system has also been demonstrated. People who lost an eye early in life show enhanced auditory localization in the horizontal azimuth compared to binocular controls (Hoover et al., 2012). Further, they do not show the typical pattern of visual over auditory dominance (i.e., Colavita visual dominance effect; Colavita, 1974) that binocular controls exhibit, but rather show equivalent auditory and visual processing (Moro & Steeves, 2012). Lastly, although people with one eye do not integrate audiovisual stimuli any differently from controls during audiovisual spatial localization, they are slower to respond when localizing visual stimuli (Moro et al., 2014).

There have been few studies investigating the morphology of sensory systems of people who have lost an eye early in life (Kelly et al., 2014, Kelly et al., 2015). Subcortically, people with one eye have an overall decrease in LGN (the visual relay station of the thalamus) volume compared to binocular viewing controls (Kelly et al., 2014). This is not surprising given the 50% deafferentation of signal to the visual system with eye enucleation. What is surprising, however, is that the LGN contralateral to the remaining eye is less reduced in volume likely from recruitment of some of the deafferented LGN cells (Kelly et al., 2014). This finding provides evidence that the visual system, even at the level of the subcortex, is vulnerable to reorganization after losing one eye early in life during the period of normal maturation (Kelly et al., 2014).

Functional neuroimaging can be used to successfully localize the MGB in humans, however, this methodology is limited by sensory stimuli and in its sensitivity (Devlin, 2006). Devlin and colleagues (2006) have been able to structurally image the MGB to resolve the functional localization concerns. Their method is now considered the gold standard for anatomical localization of the MGB and other thalamic structures. Given the existing auditory and audiovisual behavioural differences and the morphological changes in the LGN in people with one eye, we investigated whether structural changes in the MGB also exist in this group.

Methods

Participants

People with One Eye (Monocular Enucleation, ME):

Ten adult participants who had undergone monocular enucleation (ME) at The Hospital For Sick Children participated in this study (mean age = 26 years, SD = 10; 5 female). All ME participants with one eye had been unilaterally eye enucleated (5 right eye removed) due to retinoblastoma, a rare childhood cancer of the retina. Age at enucleation ranged from 4 to 60 months (mean age at enucleation = 21 months, SD = 16).

Binocular Viewing Control Participants (BV):

Fifteen binocularly intact controls with a mean age of 30 years (SD = 11; 6 female; 11 right eye dominant) were tested and reported no history of abnormal visual experience.

All participants (ME, BV) reported normal hearing, normal or corrected-to-normal acuity as assessed by an EDTRS eye chart (Precision Vision™, La Salle, IL) and wore optical correction if needed. All participants gave informed consent prior to inclusion in the study, which adhered to the tenets of the Declaration of Helsinki and was approved by York University Office of Research Ethics.

Data acquisition, processing and measurements

All scans were acquired on a Siemens MAGNETOM Trio 3 T MRI scanner with a 32-channel head coil in the Sherman Health Sciences Research Centre at York University. Proton density (PD) weighted images were processed using tools from the freely available FMRIB's Software Library (FSL; version 4.1.8) (http://www.fmrib.ox.ac.uk/fsl). All data acquisition and processing were conducted according to methods used in Kelly et al., (2014) for assessing LGN volume. Thalamic nuclei have been successfully identified using PD weighted images previously (Devlin et al., 2006; Kelly et al., 2014). See Kelly et al., (2014) for more detailed data acquisition and processing procedures.

High-resolution T_1 weighted images were acquired with the following parameters: rapid gradient echo, 1 mm^3 isotropic voxels, TR =1900 ms, TE = 2.52 ms, 256 x 256 matrix, and flip angle = 9°. Either 30 or 40 PD weighted images per participant which were acquired coronally with the following parameters: turbo spin echo, 800 μm x 800 μm in-plane resolution, slice thickness = 2 mm or 1 mm, TR = 3000 ms, TE = 22 or 26 ms, 256 x 256 matrix, and flip angle = 120°. Total scan time per participant was approximately 1.5 hours. The smaller number (30) of PD weighted images for some participants was due to time constraints.

Using FSL toolbox applications, all PD weighted images for each participant were interpolated to twice the resolution and half the voxel size using FLIRT (Jenkinson & Smith, 2001; Jenkinson et al., 2002) to increase the signal-to-noise ratio. These images were then concatenated using fslmerge and motion-corrected using MCFLIRT (Jenkinson et al., 2002). From the series of interpolated PD weighted images, a mean high resolution PD image was created per participant using fslmaths.

Following image acquisition and processing, three independent raters manually traced left and right MGB region of interest (ROI) masks three times each for each participant using the mean PD weighted image. For each rater, ROIs were merged and a median mask was created using fslmerge and fslmaths, respectively. Median masks from each of the three raters were merged together and a final median mask across raters was created. MGB volumes (left and right) were calculated for each participant from this final median mask using fslstats. All intra-rater inter-class correlations (ICC) were above 0.85 and all inter-rater ICCs were above 0.85. ICCs above 0.70 indicate that measurements were consistent both within and between raters (Cohen, 2001). These methods are the gold standard and most appropriate for evaluating thalamic structures in clinical settings (e.g. Bridge et al., 2009; Devlin, 2006; Schmitz et al., 2003). An averaged, interpolated PD weighted image with an outline of the final median ROI left and right MGB mask is shown in Figure 6.1.

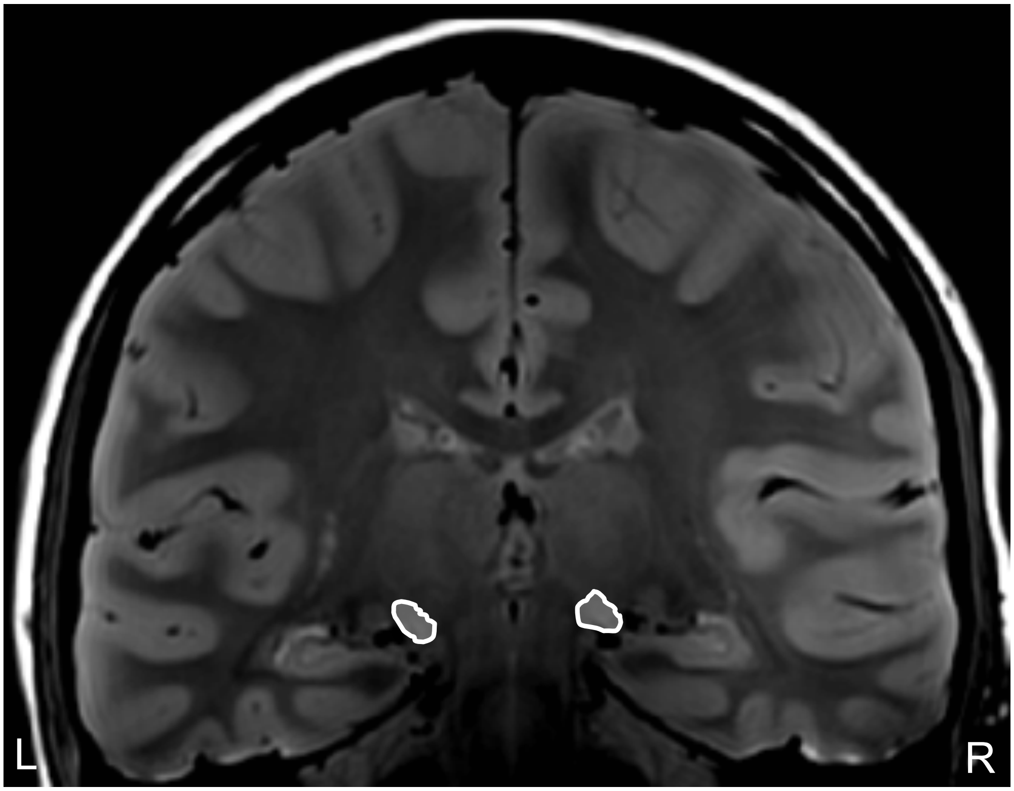

Figure 6.1. A: An averaged, interpolated PD weighted image of a typical control participant indicating the final median ROI of left and right MGB mask outlined in white.

Results

Ipsilateral vs. contralateral MGB volume

A 2 × 2 repeated measures analysis of variance (ANOVA) comparing group (ME vs. BV) and MGB side (ipsilateral vs. contralateral to remaining or dominant eye) revealed no significant interaction, $F(1,23) = 0.825$, $p = 0.373$, $\eta_p^2 = 0.035$. There was no main effect of participant group, $F(1,23) = 0.059$, $p = 0.810$, $\eta_p^2 = 0.003$, or MGB side, $F(1,23) = 0.013$, $p = 0.909$, $\eta_p^2 = 0.001$. People with one eye did not differ in MGB volume compared to controls. Figure 6.2A plots MGB volume ipsilateral and contralateral to the dominant or remaining eye of BV and ME groups respectively.

Left vs. right MGB volume

A 2 × 2 repeated measures ANOVA comparing participant group (ME vs. BV) and MGB side (left vs. right) revealed a trend toward an interaction, $F(1,23) =4.159$, $p = 0.053$, $\eta_p^2 = 0.153$. There was no main effect of participant group, $F(1,23) = 0.059$, $p = 0.810$, $\eta_p^2 = 0.003$, but there was a significant main effect of MGB side, $F(1,23) = 10.879$, $p = 0.003$, $\eta_p^2 = 0.321$. Bonferroni corrected post-hoc comparisons revealed that people with one eye had a significantly larger left compared to right MGB volume ($p = 0.002$), regardless of which eye was removed. This asymmetry was not present in the BV group ($p = 0.330$). Figure 6.2B plots left and right MGB volume of the BV and ME groups.

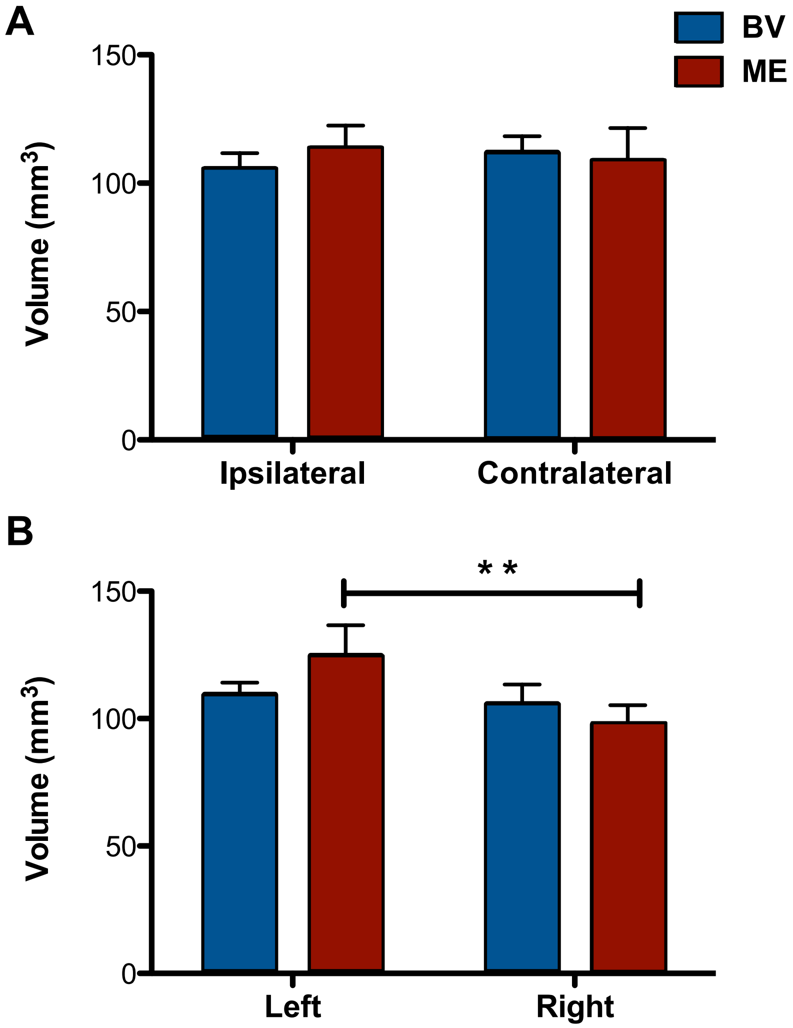

Figure 6.2. A. MGB volume (mm^3) in the ipsilateral and contralateral hemisphere to the dominant or remaining eye of BV (blue) and ME (red) groups, respectively. B. MGB volume in the left and right hemisphere of BV and ME groups.

Comparing LGN and MGB volumes

We investigated the relationship between the existing LGN volumes (Kelly et al., 2014) and our current MGB volumes. For our control participants non-parametric Spearman correlations comparing left MGB to left LGN, $r(15) = -0.25$, $p = 0.36$ and right MGB to right LGN, $r(15) = 0.13$, $p = 0.64$ were not significant. For our ME group, there is a strong positive Spearman's correlation comparing left MGB to left LGN, $r(10) = 0.73$, $p = 0.02$, while there is no significant correlation when comparing the right MGB to right LGN volumes, $r(10) = -0.03$, $p = 0.95$. Furthermore, there were no significant correlations when comparing the contralateral (to the dominant or remaining eye of participants) LGN to the contralateral MGB in both controls: $r(15) = -0.11$, $p = 0.71$ and ME group: $r(10) = 0.28$, $p= 0.43$, or when comparing ipsilateral LGN to ipsilateral MGB in both controls: $r(15) = -0.02$, $p = 0.96$ and ME group: $r(10) = -0.16$, $p = 0.66$. Figure 6.3A: plots the LGN and MGB correlations for the control participants. B: plots the LGN and MGB correlations for the ME group.

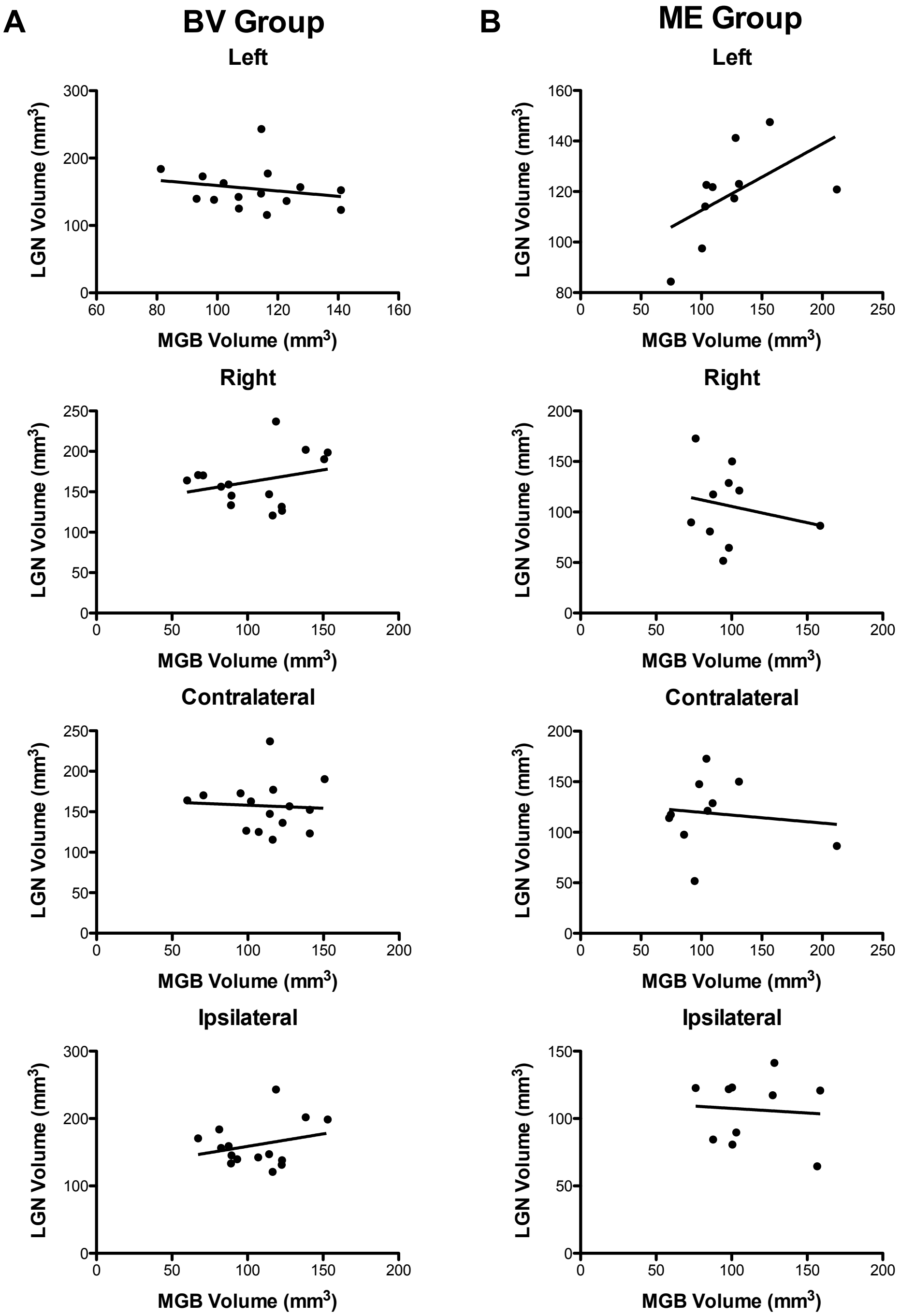

Figure 6.3. MGB volume (mm^3) correlated with LGN volume (mm^3) (taken from Kelly et al. 2014) for control participants (column A) and the ME group (column B).

Discussion

The current study used structural MRI to anatomically localize and measure the MGB volume in people with one eye and binocularly intact controls. Overall, people with one eye displayed an asymmetry in MGB volume with a larger left than right MGB, regardless of which eye was enucleated. Binocularly intact controls did not display an asymmetry.

Although traditionally viewed as an audiocentric structure, rat studies have shown that subnuclei of the MGB also receive some visual input (Linke et al., 2000; Komura et al. 2001, 2005). In humans, participants presented with low intensity visual stimuli paired with an auditory tone show increased behavioural sensitivity and functional activation in the MGB, indicating crossmodal influences on the MGB (Noesselt et al., 2010). These crossmodal influences on the MGB might be driven through corticothalamic feedback mechanisms, which in turn may influence multisensory interactions (Noesselt et al., 2010). In addition, people with one eye have superior sound localization abilities (Hoover et al., 2012) supporting the documented coding of sound localization in the MGB (Samson et al., 2000). Given that our patient population is missing half of the retinal inputs to the visual system, the MGB asymmetry observed in people with one eye may reflect neural reorganization at the subcortical level during postnatal maturation. This is consistent with the cortical changes that have been found in this patient group described below.

Recently, Kelly and colleagues (2015) found that people with one eye exhibited significantly larger cortical surface area in auditory supramarginal and superior temporal regions, specifically in the left hemisphere compared to binocularly intact controls. These regions are implicated in short-term memory of auditory information (Paulesu et al., 1993) and audiovisual multisensory integration (Beauchamp et al., 2004), respectively, indicating reorganization in cortical areas outside of primary visual regions following early monocular enucleation (Kelly et al., 2015). The cortical surface area, LGN and the present findings complement auditory and audiovisual behavioural data in this monocular enucleation group showing equal processing of paired auditory and visual signals (Moro & Steeves, 2012), better sound localization (Hoover et al., 2012) and optimal audiovisual integration (Moro et al., 2014) compared to controls. It is possible that the increase in cortical surface area in left hemisphere auditory and multisensory regions with monocular enucleation is reflected in strengthened corticothalamic feedback to the left MGB and has lead to the presently observed MGB volume asymmetry.

The relationship between the previously published LGN and the present MGB volumes in both controls and people with one eye were correlated. If the larger MGB volume were limited by space constraints then the MGB asymmetry should be related to a decrease in size of the LGN and one would predict a negative correlation. We found no relationship in any comparison except for a strong *positive* correlation between the left MGB and left LGN in people with one eye. This signifies that a larger left MGB is related to a larger left LGN in people with one eye and rules out the space constraints prediction. A larger left MGB cannot be solely explained as a harvesting of unused subcortical real estate since a larger left MGB is associated with a larger left LGN. Instead, a strong positive correlation indicates overall increased plasticity across sensory systems that is not restricted by subcortical space confines but rather is related to corticothalamic feedback from left hemisphere cortical areas that have larger surface area (Kelly et al., 2015) thereby demonstrating multi-level reorganization of sensory systems.

Multisensory events, such as audiovisual speech processing, have been reported to involve thalamic modulation (Baier et al., 2006; Cappe et al., 2009; Musacchia et al., 2007) and the MGB responds preferentially to more complex speech-like structure (Jiang, 2013). People with dyslexia show a reversed hemispheric asymmetry to our current findings (i.e., smaller left versus right MGB) (Galaburda, 1994). The left hemisphere of cortex plays a central role in language processing due to its analysis of fast temporal auditory transitions (Galaburda, 1994). Phonological abnormalities in people with dyslexia may be reflected in adverse left hemisphere cortical reorganization contributing to the reverse MGB asymmetry found in dyslexia (Galaburda, 1994). People with one eye have mild face recognition deficits compared to binocular and monocular viewing controls (Kelly et al., 2012). It is possible that as a consequence of their mild face-processing deficit, the brain of people with one eye has reorganized to emphasize speech and language for identifying individuals, which could lead to specific structural changes to language areas in the left hemisphere of the brain. Future studies investigating behavioural measures of speech and language processing in this group would be an ideal extension of these anatomical data.

Summary

The MGB volume asymmetry in people with one eye may represent increased interactions between the left MGB and primary auditory cortex. This interaction could contribute to increased auditory and other aspects of left hemisphere-dominant processing, including language. We observed overall multisensory plasticity with a relationship showing increasing plasticity in the visual LGN and the auditory MGB, reflecting subcortical reorganization as compensation for the loss of one half of visual inputs to the brain early in life.

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CHAPTER VII

GENERAL DISCUSSION

This dissertation investigated audiovisual processing in people who have had one eye removed early in life. I sought to expand our understanding of the effects of losing one eye early in life on the development of audiovisual processing both behaviourally and in terms of underlying neural structural representation. I asked whether people with one eye show altered, possibly enhanced, processing of audiovisual information as cross-modal sensory compensation for the loss of one eye. In each experiment, I compared this unique group to binocular controls viewing either binocularly or monocularly (with one eye patched). Overall, throughout the 5 experimental chapters presented in this dissertation, I demonstrated that compared to binocular and eye-patched control groups, people with one eye do not show the same patterns of audiovisual processing and they also have altered subcortical structural representation suggesting behavioural and structural adaptations for the loss of one eye early in life.

Summary

Chapter II investigated behavioural performance in people with one eye during audiovisual tasks with low-level stimuli. This chapter investigated whether losing one eye early in life impacts the processing of temporally disparate auditory and visual stimuli. Specifically, does early visual deprivation from eye enucleation alter the temporal binding window of low-level audiovisual flash and beep stimuli and does it affect susceptibility of the double flash illusion.

In Experiment 1a, I measured the temporal binding window (TBW) in people with one eye compared to binocular and eye-patched viewing controls. I hypothesized that people with one eye would have a more precise (narrower) TBW compared to controls since it has been previously shown that people with one eye have more accurate sound localization (Hoover et al., 2012). People with one eye did not differ in the width of their temporal binding window compared to binocular and eye-patched viewing controls. However, they had longer response latencies compared to binocular viewing controls indicating a longer processing time for this task. Eye-patched controls' response latencies were intermediate to the two other groups.

In Experiment 1b, I measured the susceptibility to the double flash illusion, an illusion where multiple flashes of light are perceived when a single flash of light is paired with multiple tones. I compared people with one eye to binocular and eye-patched viewing controls. I hypothesized that people with one eye would have reduced susceptibility to the double flash illusion if results from Experiment 1a indicated a narrower TBW compared to controls. In fact, people with one eye were less susceptible to the double flash illusion compared to both binocular and eye-patched viewing controls. In this task, people with one eye responded as quickly as binocular and eye-patched viewing controls.

Taken together, these results suggest that susceptibility to the double flash illusion may not simply reflect the width of the temporal binding window. These results provide evidence that people with one eye have adapted audiovisual integration subsequent to the reduction of visual input from one eye and that adaptations may differ based on task requirements. Further, their audiovisual adaptation reduces susceptibility to audiovisual illusions.

Chapter III continued to investigate audiovisual behaviour in people with one eye using low-level stimuli but in this instance, in the depth plane. This chapter investigated whether people who have had one eye removed early in life demonstrate the same susceptibility to audiovisual dynamic visual capture in the depth plane, as do binocular and eye-patched viewing controls. This chapter builds on the studies conducted in Chapter II, with the investigation of the perception of low-level auditory beep and visual flash stimuli, and expands the investigation to include a layer of ecological validity by incorporating the depth plane. For the current study, I hypothesized that people with one eye will not have the same susceptibility to dynamic visual capture compared to controls given their previously documented mild impairments to motion processing, specifically the overestimation of time to collision (Steeves et al., 2000) and lack of visual dominance (Moro & Steeves, 2012; 2013) found in this group. Similar to both binocular and eye-patched viewing controls, people with one eye perceived the direction of the auditory signal to be moving in the direction of the incongruent visual signal despite being asked to respond to the auditory signal alone. These results are consistent with previous research in healthy controls that observed a robust dynamic capture effect, where the perceived direction of motion of the auditory signal was influenced by an ignored visual stimulus moving in the opposite direction (Harrison, 2012; Jain et al., 2008; Kitajima & Yamashita, 1999). In addition, people with one eye showed no difference in reaction time or accuracy compared to both control groups for any of the conditions (unimodal visual looming and receding, unimodal auditory looming and receding, congruent looming and receding and incongruent looming and receding). Furthermore, people with one eye showed similar magnitude of dynamic visual capture compared to both control groups indicating that there is no difference between groups in how the visual stimulus influences the perception of the auditory stimulus. Increased weighting (as expressed through dynamic visual capture) for looming visual stimuli confers an ecological advantage since an approaching object could make contact with the observer in an adverse way.

Taken together, these results expand upon the evidence found in Chapter II, that suggests that people with one eye do not differ in the width of their TBW but are also not susceptible to the double flash illusion. People with one eye might alter their perception of low-level auditory and visual stimuli since behavioural performance in this group is not consistent across different tasks. Previous studies have indicated that people with one eye are not visually dominant (Moro & Steeves, 2102; 2013) therefore it was predicted that they should also not demonstrate visual capture of audition, however this is not the case. The alteration of how auditory, visual and audiovisual stimuli are perceived may be a result of task requirements. The introduction of competing auditory and visual stimuli (in the form of an illusion, such as the double flash or visual capture) will affect the performance of people with one eye differently each time perhaps through the direction of attention. In the current study, directing attention towards vision may alter the perception of unimodal visual stimuli despite previous evidence indicating non-dominance of vision in this group (Moro & Steeves, 2012; 2013). For example, a looming visual stimulus that is interpreted as being potentially adverse is perceived as being dominant, similar to controls. Visual information is more precise in timing and spatial location therefore making it more veridical. Directing attention based on task requirements may contribute to making the perception of unimodal stimuli more veridical even if it has previously shown to be non-dominant in a different task. This may also contribute to the decreased perception of the double flash illusion but is not reflected in the simple detection task of the TBW in Chapter II.

<u>Chapter IV</u> investigated behavioural performance in people with one eye during an

audiovisual task, using higher-level face and voice stimuli. This chapter builds on the studies conducted in Chapters II and III by adding additional ecological validity to the auditory and visual stimuli through the use of faces and voices. The current study specifically investigated how people with one eye perceive the McGurk effect, an audiovisual illusion where a new syllable is perceived when visual lip movements do not match the auditory sound clip (McGurk & MacDonald, 1976). I hypothesized that there would be a decreased or lack of McGurk effect in participants with one eye given the results of previous research in this group, especially their lack of visual dominance (Moro & Steeves, 2012; 2013). People with one eye perceived the illusory McGurk effect less often than binocular viewing controls. They did not differ from either control group in terms of accuracy for unimodal visual, unimodal auditory and congruent audiovisual stimuli. Additionally, they showed no difference in reaction time compared to both control groups for any of the conditions. Finally, the eye-patched viewing controls perceived the illusory McGurk syllable less often than binocular viewing controls indicating a modulation of the McGurk effect with eye patching. Overall, these results show a more veridical perception of unimodal sensory inputs during higher-level audiovisual events and less susceptibility to the audiovisual illusion with long-term visual deprivation in people with one eye and a small effect in controls with short-term visual deprivation from eye patching.

Taken together, the results of the current study extend the evidence observed in Chapters II and III indicating that people with one eye might alter their perception of high-level audiovisual stimuli during illusory tasks through directing attention. This alteration of perception is similar to that observed for low-level audiovisual stimuli during illusory tasks. These adaptations may be driven by attentional mechanisms similar to those responsible for the decreased perception of the double flash illusion in Chapter II and the visual dominance observed in the looming stimuli used in Chapter III.

Chapter V builds on the studies conducted in Chapter IV by increasing the ecological validity through the use of audiovisual stimuli to identify people and objects. This study investigated behavioural performance in people with one eye during an audiovisual task for person and object identity recognition, using higher-level person (face/ voice) and object (car/ car horn) stimuli.

Experiment 4a quantified person recognition for faces, voices and face-voice pair combinations in people with one eye compared to binocular and eye-patched viewing controls. I hypothesized that people with one eye will demonstrate a deficit in person identification given previous results that indicate mild face perception impairment (Kelly, Gallie & Steeves, 2012). People with one eye and eye-patched controls showed greater sensitivity to voices compared to the binocular controls. Unlike binocular viewing controls, people with one eye and eye-patched viewing controls did not have increased interference when voice information was added to bimodal stimuli. People with one eye did not show a difference in performance compared to both control groups when visual information was added to bimodal stimuli. These results suggest that the increased sensitivity to unimodal voices might serve as an adaptation to the reduction of visual input from one eye in general. The lack of change in bimodal sensitivity upon the addition of visual information between groups indicates that the additional information from the partially deprived sense in people with one eye did not hinder (or help) their performance and did not differ from either control group. Binocular viewing controls’ preference for congruently paired stimuli suggests that they likely made their recognition judgments based on their dominant sensory modality (vision) more often than did eye-patched viewing controls and people with one eye.

Experiment 4b quantified object recognition for cars, car horns and car-horn pair combinations in people with one eye compared to binocular and eye-patched viewing controls. I hypothesized that people with one eye will not have a deficit in object identification. There was no difference in performance between groups for unimodal visual (car), unimodal auditory (horn) and bimodal (car-horn) stimuli sensitivity. Furthermore, people with one eye do not demonstrate greater interference or enhancement compared to controls when their bimodal sensitivity score was compared to their unimodal visual and unimodal auditory sensitivity score, respectively. All three groups were better at identifying bimodal congruent compared to incongruent stimuli. The auditory advantage demonstrated by people with one eye is specific to person identification and does not generalize to object identification.

Results were compared across Experiment 4a and 4b in order to identify whether audiovisual perception of person identity is unique compared to object identity. I hypothesized that results will differ in people with one eye for person identification compared to controls but not for object identification. Only the binocular viewing controls' behaviour was enhanced to a greater degree by adding the visual stimulus to the auditory stimulus (visual effect score). This effect was limited to person identity but not object identity, indicating a form of visual dominance consistent with other visual dominance effects such as the Colavita effect (Moro & Steeves, 2012). Binocular viewing controls use visual information from faces to enhance person identification more than the visual information from cars to enhance object identification. Eye-patched viewing controls and people with one eye did not differ across tasks on their visual effect score suggesting a lack of visual dominance, consistent with previous research (Moro & Steeves, 2012). All participant groups showed greater interference on their auditory effect score, where additional information provided by the auditory stimulus more greatly interfered with bimodal sensitivity for person identification but not for object identification. This result indicates that the additional information from the voice hindered the sensitivity for person identification greater than the additional information from the horns for object identification.

Taken together, the results of the current study extend the evidence observed in Chapters II, III and IV indicating that people with one eye might alter their perception of both low-level and high-level audiovisual stimuli. These observed differences in perceptual behaviour have been demonstrated in tasks involving both low-level and high-level illusory stimuli, as well as, low-level and high-level ecologically relevant stimuli. Similar to the previous experiments in this dissertation, these adaptations may be driven by attentional mechanisms that may contribute to making the perception of unimodal stimuli more veridical.

Chapter VI investigated subcortical volume of the auditory nucleus of the thalamus in people with one eye compared to binocular viewing controls. This chapter builds on the behavioural studies conducted in Chapters II, III, IV and V by investigating whether the differences in behavioural performance observed in people with one eye are reflected in subcortical structural differences similar to those observed in the lateral geniculate nucleus

(LGN), anterior visual system and cortical surface area (Kelly et al., 2014; Kelly et al., 2015). The current study used structural MRI to anatomically localize and measure the medial geniculate body (MGB) volume. I hypothesized that people with one eye would display morphological changes in the form of increased MGB volume bilaterally, which would reflect the auditory behavioral changes that have been observed to date. People with one eye displayed an asymmetry in MGB volume with a larger left than right MGB, regardless of which eye was enucleated. Binocularly intact controls did not display an asymmetry.

Taken together, the results of the current study provide a better understanding of the neural correlates underlying the behavioural changes that have been previously observed in people with one eye.

Overall, my behavioural data in conjunction with my structural neuroimaging data have enabled further exploration of the auditory, visual, and audiovisual processing mechanisms in this rare patient group. The role of two over-arching elements, attention and white matter connectivity, should be considered during the global interpretation of these results.

The role of attention

We are continuously inundated with multisensory perceptual stimuli in our environment. Through the use of attention, relevant stimuli can be dynamically selected from the available array of information in our environment, facilitating their processing (Talsma et al., 2010). Both bottom-up and top-down mechanisms drive attentional selection (Theeuwes, 1991). Bottom-up attentional mechanisms are stimulus driven, typically employed when there is minimal competition to focus elsewhere, allowing the stimulus to capture attention automatically (Talsma et al., 2010). Top-down attentional mechanisms are goal driven, typically employed when information at early stages of processing is influenced by information from higher stages of processing (Gilbert & Sigman, 2007). Top-down attentional mechanisms are driven by how relevant a stimulus is to an observer's goals and intentions both conscious and subconscious (Talsma et al., 2010). Top down attention contributes to multisensory integration since each individual modality is competing for processing resources, reducing the saliency of each stimulus (Talsma et al., 2007; Talsma et al., 2010; Van Ee et al., 2009).

It is likely that top-down modulation from attention, which is known to contribute to and interact with perception, plays a role in the way in which people perceive bimodal stimuli (see Murray et al., 2016, for a review). Recent studies have provided evidence for the influence of top-down attention on multisensory integration. When attention is directed to a secondary task, susceptibility to the McGurk effect is reduced (Alsius et al., 2005; Alsius et al., 2007). This suggests that a reduction in integration is possible through manipulating attention since processing resources are diverted away from individual sensory inputs for a multisensory event (Talsma et al., 2010). This indicates that decreased competition between neural resources facilitates audiovisual integration; however, introducing a diversion of attention (through a secondary task) increases competition between neural resources hindering the integration processes (Alsius et al., 2007; Talsma et al., 2010). It is possible that people with one eye experience a similar form of attentional manipulation that results from subconscious redirection of attention due to limited processing resources resulting from the loss of 50% of their visual input to the brain. This may be especially true during ambiguous multisensory presentations or in ecologically important conditions, in an attempt to better understand the complex multisensory information in the world.

The inconsistent audiovisual behavioural performance observed throughout this dissertation following early postnatal visual deprivation compared to binocular and eye-patched viewing controls is dependent on whether stimulus expectations are met (i.e., illusory vs. non-illusory). This indicates that dynamic top-down attentional mechanisms influence multisensory processing in this group based on the task expectations (Talsma et al., 2010). Perceptual estimates reflecting the behavioural and sensory context are dynamically updated as opposed to being fixed to exclusively bottom-up attentional processing (Gilbert & Sigman, 2007). Feedback connections from higher to lower cortical areas likely mediate this dynamic functional switching (Gilbert & Sigman, 2007). Such audiovisual adaptation would affect the way in which complex multisensory events are processed and the maturation of underlying brain mechanisms. This attentional shift might result in a reduction in the perception of audiovisual illusions as demonstrated in Chapter II and IV, and is consistent with previous studies showing a lack of visual dominance (Moro & Steeves, 2012; 2013).

It is possible that through dynamic top-down attention, people with one eye have a more veridical perception of unimodal sensory inputs that are influenced based on ecological importance of the task (a form of task expectation). This can be observed in Chapters III and V where people with one eye direct attention towards different unimodal senses but still perform optimally, similar to binocular viewing controls. In Chapter III, people with one eye may have directed attention towards the visual modality, providing a greater opportunity to gather as much reliable information about the approaching or receding stimulus as possible, which could provide safety in the life-threatening situation of an approaching object. In Chapter V, people with one eye demonstrated increased sensitivity to voice stimuli, contributing to accurate person identification and perhaps accounting for mild holistic face processing deficits observed previously.

The role of white matter connectivity

People who had an eye removed early in life have degeneration of the anterior visual system, including decreased optic chiasm volume and width compared to binocular controls (Kelly et al., 2014). As is expected, when 50% of the signal to the visual system is deafferented after one eye is removed, they also have an overall decrease in LGN volume compared to binocular controls (Kelly et al., 2014). Surprisingly, the volume of the LGN contralateral to the remaining eye is less reduced likely due to the recruitment of some of the deafferented LGN cells (Kelly et al., 2014). People with one eye have also been shown to exhibit increases in surface area and gyrification in visual (V1 and inferior temporal cortex; contralateral to the remaining eye), auditory (supramarginal) and multisensory (superior temporal, inferior parietal, superior parietal) cortices compared to binocular viewing controls (Kelly et al., 2015). The results from these structural studies, as well as, those of Chapter VI indicating asymmetrical MGB volume in people with one eye compared to binocular viewing controls, provide evidence that even at the subcortical level, reorganization of the visual system is possible after losing one eye early in life.

There are several mechanisms that might support the structural changes observed in people with one eye including: Wallerian degeneration, Wilbrand's knee (Horton, 1997), neural recruitment of deafferented cells (Grigonis et al., 1986; Rakic, 1981), corticothalamic feedback (Bartlett, 2013; Horton & Hocking, 1998; Sloper, 1993; Toosy et al., 2001; Zhang et al., 1997) and impaired synaptic pruning (Godement et al., 1987; Grigonis et al., 1986). It has been shown that surface area and gyrification (observed to be increased in visual, auditory and multisensory cortices in people with one eye) are influenced by changes in white matter (Hilgetag & Barbas, 2006; Van Essen, 1997). Additionally, white matter tracts continue to develop throughout childhood and into adolescence, increasing the likelihood that removing one eye early in life will have a significant impact (Barnea-Goraly et al., 2005; Gao et al., 2009).

Recently, diffusion tensor imaging (DTI) and probabilistic tractography was conducted in people with one eye to assess white matter of the visual system compared to binocular viewing controls (Wong et al., 2017). Mean diffusion parameters were measured bilaterally including fractional anisotropy (FA, a scalar value from 0 to 1 that describes the degree of directionality, or anisotropy, of the diffusion process), mean diffusivity (MD, the average rate of diffusion within a voxel), axial diffusivity (AD, the principal eigenvalue of the diffusion tensor [λ_1], representing the degree of diffusion parallel to the axon) and radial diffusivity (RD, the average of the second and third eigenvalues of the diffusion tensor [$\lambda_2 + \lambda_3/2$], representing the diffusion perpendicular to the axon). Overall, significant differences for the mean diffusion parameters observed consistently for tracts contralateral to the removed eye, were observed in the optic radiations, V1-LGN projections and interhemispheric V1 projections of people with one eye compared to binocular viewing controls (Wong et al., 2017). These asymmetrical changes were likely a reflection of the differences observed in the LGN volume and optic tract contralateral to the removed eye previously demonstrated in this group (Kelly et al., 2014). Overall these results indicate that early monocular enucleation has long-term effects on white matter structure in the visual pathway that results in reduced fiber organization in tracts contralateral to the removed eye. These differences may be driven or influenced by the previously observed structural changes in this group. The differences in behavioural performance reported for this group throughout this dissertation (Chapters II – IV) and in previous research (Moro & Steeves, 2012; 2013; Moro, Harris & Steeves, 2014) may also be accounted for by the changes in white matter structure. The altered white matter tracts may indicate altered pathways of visual information transmission that may be reflected in the increased response times observed in this group for some audiovisual tasks. Previous research indicates the possibility of a relationship between white matter structure and behavioural function. A positive correlation has been demonstrated between reaction time on a visuospatial task and FA in the right optic radiation, right posterior thalamus and right medial precuneus (Tuch et al., 2005). Furthermore, for an object recognition task, higher FA has been associated with shorter reaction times within the posterior part of the corpus callosum, whereas longer reaction times are correlated with increased FA in the anterior part of the corpus callosum (Baird et al., 2005; see Roberts et al., 2013, for a review).

Limitations

The methods for each experiment presented in this dissertation were carefully planned and based on previously established methods. Each study was carefully controlled to reduce the occurrence of potential confounds. Some unavoidable limitations due to the patient group and neuroimaging methodology are discussed in the following sections.

Patient Group. The patients used in each of my studies were people who had one eye removed early in life due to childhood retinoblastoma. They were recruited from a database of patients acquired through collaboration with The Hospital for Sick Children. All of the patients tested throughout my dissertation had their eye removed early in life, typically before 2 years of age. This indicates that their eye was removed before the maturation of their visual system. An important limitation to consider with this group is that it is impossible to control for the exact timing of visual deprivation. The cancerous tumor can develop at any point postnatally and may impede the fovea prior to the eye being removed. This indicates that some patients may have also had period of abnormal vision (typically 6 months at most) prior to enucleation. It is not likely that this limitation should pose any issue when interpreting the results presented in each of my studies, as they were tested later in life as adults, since I was interested in studying the long-term effects of early visual deprivation.

Additionally, as is typical in studying patients with rare diseases, it is difficult to obtain a large sample size. Sample size for the patient group in each of my studies ranged from 7-11 participants. I was only able to recruit a sample size greater than 10 participants in two experiments (Chapter V). In order to compensate for this, I ensured that the patient group was compared to larger control samples consisting of at least twenty participants in each of the binocular and eye-patched viewing groups. Each patient was approximately age and sex matched with participants in both control groups.

<u>Structural MRI.</u> It is impossible to know the definitive causes of the structural changes observed in the patient group in Chapter VI of this dissertation, as well as, in previous studies (Kelly et al., 2014; Kelly et al., 2015; Wong et al., 2017). Additionally, structural neuroimaging methods do not reveal changes in functional activation. In Chapter VI, MGB volumes were visually determined by three independent raters' manual tracing of bilateral MGBs. It cannot be determined how the cells in the MGB respond to visual or

auditory input based solely on these structural measures. Since brain function depends partly on brain structure, function can be inferred based on morphological measures. For example, within the visual cortex, functional boundaries of V1 and V2 are accurately predicted by anatomical boundaries (Fischl et al., 2008; Hinds et al., 2008; 2009). Based on the increases in surface area and gyrification found in visual, auditory and multisensory cortices in people with one eye (Kelly et al., 2015), as well as, altered white matter connectivity (Kelly et al., 2015; Wong et al., 2017), it can be speculated that altered audiovisual processing reported for the people with one eye may reflect the increases in morphology found in this group, however, these results must be interpreted with caution.

Future research

There are many possible directions in which the studies presented in this dissertation could be developed. Three directions that will contribute important evidence to answer emerging questions include: expanding structural and functional MRI, attention and age of enucleation.

Structural and Functional MRI. An emerging question involves the relationship between the previously published behavioural and structural findings in this group (Moro & Steeves, 2012; 2013; Moro, Harris & Steeves, 2014; Kelly et al., 2014; Kelly et al., 2015; Wong et al., 2017), as well as, those presented in this dissertation. Structural differences in people with one eye compared to binocular viewing controls include: decreases in LGN volume, increases in surface area and gyrification found in visual, auditory and multisensory corticies, altered white matter connectivity and asymmetrical MGB volume (Kelly et al., 2014; Kelly et al., 2015; Wong et al., 2017). Behavioural evidence of altered audiovisual processing include: lack of visual dominance, optimal but slower audiovisual spatial integration, normal but slower TBW, decreased perception of audiovisual illusions including the double flash illusion and McGurk illusion, normal visual capture of audition, impaired person but not object recognition (Moro & Steeves, 2012; 2013; Moro, Harris & Steeves, 2014). Future research should continue to investigate structural and functional activity in cortical regions associated with auditory and multisensory (audiovisual) processing. Specifically, functional MRI will help draw connections between altered structure and function. These experiments can investigate whether people with one eye have similar sized regions of activation and intensity of activation for auditory, visual and audiovisual stimuli as binocularly viewing controls. Furthermore, including a group of monocular viewing (eye-patched) control participants in these studies would contribute to investigating the behavioural differences (such as decreased perception of the McGurk effect) observed in this group at the cortical level. The results would help us compare and understand the behavioural differences observed in people with one eye and eye-patched controls and determine whether the differences are a result of the brain receiving a decreased amount of visual information or if long-term deprivation affects cortical activation. I would hypothesize that auditory activation may also be observed in visual regions that have been deafferented similar to people with early blindness (Merabet et al., 2009; Collignon et al., 2009). I predict that the activation observed in people with one eye may not be as clean given that they still have afferent projection of visual information to V1 from their remaining eye. Furthermore, if there is an increased representation of auditory activation in visual areas I predict an increase in activation and size in multisensory areas, specifically the STS.

Attention. A second emerging question involves the influence of attention on audiovisual processing in people with one eye compared to binocular and eye-patched viewing controls. Future studies manipulating perceptual load or stimulus features, while simultaneously manipulating top-down attentional factors, would be a useful direction in which to begin. Studies reinvestigating paradigms where behavioural performance in people with one eye differed from controls for example, audiovisual illusions such as the double flash illusion, the McGurk effect (Chapter II and IV) and visual dominance (Moro & Steeves 2012; 2013) while incorporating the manipulation of overall attentional goals would contribute useful evidence to this research area. An ideal initial study would direct a participant's attention towards a specific modality (such as audition or vision) through a secondary task that would be integrated into an existing audiovisual task such as the Colavita visual dominance paradigm. I would hypothesize that manipulating attention using top-down attentional factors would influence the behavioural performance of people with one eye to be similar to that of binocular viewing controls, as both groups will have a "levelled playing field" in terms of equal allocation of attention due to the addition of a secondary task. It is possible that the intentional manipulation of attention might override the hypothesized dynamic redirection of attention that might account for the current differences in perception as accommodation for the loss of 50% of the visual input to the brain.

Age of Enucleation. A third emerging question involves the influence of age at enucleation and time since enucleation. It would be beneficial to conduct both behavioural and neuroimaging studies in a group of patients who had one eye removed later in life after the critical periods of development. The early enucleation group studied in this dissertation had their eye removed before the critical periods for visual development and they were tested later in life as adults. This group therefore, also has had a long time to adapt to living with one eye over the course of their life. Comparing the results of the current patient group, who had one eye removed before the visual system was fully mature, with those of a group of people who had their eyes removed later in life after the visual system was fully mature and have subsequently lived for a shorter time since enucleation, will contribute evidence to determine whether the current accommodations are a result of reorganization during development or if reorganization occurs over time since enucleation. To date, our group has studied one late enucleated participant. This participant exhibited larger decreases and no asymmetry in LGN volume and decreases in cortical thickness (unlike participants who had their eye removed early in life) (Kelly et al., 2014; Kelly et al., 2015). These results indicate that after the critical period for development plasticity of the visual cortex is present, but weaker (Kelly et al., 2015). It would be beneficial to further investigate these findings to see whether they will hold when comparing a group of participants enucleated late in life to participants enucleated early in life and binocular viewing controls. I would hypothesize that with increased age at enucleation and decreased time since enucleation less cortical reorganization will be observed through structural and functional MRI, as well as, decreased performance on behavioural tasks given the short amount of time for adaptations to develop.

Future application of research

The adaptive capacity of the central nervous system includes its ability to modify its own structural organization and corresponding function of neural pathways in the brain. Behavioural enhancements observed in non-visual senses in people with congenital blindness suggest underlying physiological changes within the systems responsible for these senses. For example, congenitally blind individuals have shorter response times for auditory discrimination tasks (Röder et al., 1999), faster processing of language (Röder et al., 2002), enhanced sound localization (Lessard, Paré, Lepore & Lassonde, 1998) and tactile perception (Sathian, 2000) compared to sighted individuals. Additionally, the visual cortex is recruited or reorganized by other sensory systems in people with congenital blindness. This notion is supported by recent neuroimaging studies of auditory processing (Merabet et al., 2009; Collignon, Voss, Lassonde & Lepore, 2009) and sound localization (Weeks et al., 2000), as well as, tactile perception and Braille reading (Kupers et al., 2007; Sadato et al., 1996; Cohen et al., 1997; Buchel et al., 1998) which recruit visual cortices for these other sensory systems. Each study shows activation of the visual cortex for sensory stimuli normally processed elsewhere in the brain. These findings demonstrate that in cases of complete visual deprivation, it is possible for other intact sensory systems to adapt to and compensate for the loss of vision. Sensory substitution exploits this adaptive plasticity, which benefits the remaining intact senses, to not only compensate for the visual loss but also in an attempt replace it by using other senses to code visual information and substitute for this lost sense.

In sensory substitution of sight, an artificial receptor relays visual information to the brain through another sensory system (Bach-y-Rita, 1969). The brain uses the information from an artificial receptor in place of the information usually transmitted from the eyes so that the user can perceive visual information. Bach-y-Rita was the first to describe sensory substitution where he implemented a 20x20 array of 400 solenoid stimulators built into a dental chair, that vibrated against the skin of an individual's back (Bach-y-Rita, 1969). Visual spatial information was translated to the end user via a pattern of tactile vibrations (Bach-y-Rita, 1969). Information that is gained from one sensory modality can reach brain structures physiologically related to the substituted sensory modality. Sensory substitution occurs across sensory systems, for example, sensory substitution of sight using either touch or hearing.

Audition is an easy and discrete sensory system to use as an interface for vision since standard sound emitting devices, such as earphones, would be sufficient to use. The auditory system is easily able to process and interpret complicated patterns of sounds such as speech or music in noisy environments (Capelle et al., 1998). Audition can be compared more closely to vision given its exceptional frequency and intensity discrimination thresholds resulting in the ability to process a large volume of information (Capelle et al., 1998). A current successful sensory substitution device called the vOICe converts visual information into an auditory "soundscape" (Amedi et al., 2007). In this sensory substitution system, the columns of a visual image are translated into sounds from left to right, frequency of the sound is represented by the height of a pixel on the image and amplitude by the brightness of the pixel (Amedi et al., 2007). The lateral-occipital tactile-visual (LOtv) area that is normally activated when objects are recognized by vision or touch is also activated by the vOICe in sighted and blind users (Amedi et al., 2007). This suggests that the LOtv is driven by neural reorganization in users brains allowing this area to be activated through audition (Amedi et al., 2007). The vOICe has achieved the highest measurement of visual acuity with any visual rehabilitation approach demonstrated by congenitally blind users, exceeding the World Health Organization's designation of legal blindness, with an acuity threshold of 20/200 (Striem-Amit et al., 2012).

The accuracy level reached throughout the development of sensory substitution devices demonstrate the potential applicability of using sensory substitution devices for daily tasks that require fast, accurate reaching movements, such as reaching for a glass of water. Evidence of cortical reorganization in blind users showed that the brain has been able to advantageously alter their ability to process tactile or auditory information in cortical areas normally designated for vision thereby allowing them to actually perceive the visual information relayed to them in a meaningful way.

The advantages afforded through the use of a sensory substitution system in people with congenital blindness can be modified and applied towards individuals with partial blindness. People with one eye are an ideal representation for partial sensory deprivation since there is no competing visual information present from the affected eye. The current studies presented in this dissertation and future studies focusing on people with one eye will contribute evidence towards indicating whether there exists an advantage towards using one sense over another (for example better sound localization; Hoover et al., 2012). The advantageous sense can be exploited in a similar way to provide partial sensory substitution or sensory enhancement to learn to accommodate for specific deficits in visual processing that exist through the loss of binocularity such as stereopsis (Steeves et al., 2000) and motion perception (Steeves et al., 2002). These methods may then be modified and applied to less severe forms of visual deprivation such as patients with amblyopia and cataracts where a comprehensive training program could be created to teach individuals how to use auditory and audiovisual information to the best of their abilities.

Conclusion

My dissertation explored audiovisual processing in a rare patient group who had one eye removed early in life compared to binocular viewing controls viewing both binocularly or monocularly with one eye patched. Through 6 behavioural studies I compared the performance of audiovisual processing using progressively more ecologically important stimuli from low level flashes and beeps (Chapter II), low-level illusory (Chapter II), low-level looming (Chapter III), illusory face and voice (Chapter IV) and person and object recognition (Chapter V). My final study used structural neuroimaging to investigate the structure of the predominately auditory processing thalamic nucleus of the MGB (Chapter VI). These behavioural data in conjunction with these structural neuroimaging data have enabled further exploration of the auditory, visual and audiovisual processing mechanisms in this rare patient group. I have shown that people with one eye may not process sensory information in the same way as binocular and eye-patched controls. They do not show the same robust pattern of perceiving audiovisual illusions compared to controls for tasks using both low-level and high-level stimuli. They do not differ on performance for detection of low-level audiovisual stimuli but in order to achieve this, detection takes longer. When ecological validity is important, as observed with low-level looming stimuli, people with one eye also do not differ from controls. They are more sensitive at perceiving voices for person recognition but do not differ compared to controls for object recognition. Finally, they show an asymmetry in MGB volume that is not found in controls.

Taken together, these results contribute evidence that people with one eye undergo a reorganization of sensory processing in the brain possibly modulated by top-down attentional mechanisms and white matter connectivity. Perhaps it would be adaptive to increase sensory ability to subconsciously choose which stimulus input will be perceived to be most reliable dynamically, depending on the stimulus presentation at hand. These accommodations may serve as an adaptive compensatory mechanism for the loss of half of the visual input to the brain. This information can lead us to better understand sensory plasticity, in addition to the sensory deficits experienced by people with one eye, which will facilitate prediction of the outcome from the early loss of one eye on multisensory perception. Overall, the results presented in this dissertation substantiate using this group as a model to inform how to accommodate and maintain the health of less extreme forms of visual deprivation, as well as, to promote overall long-term visual health.

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APPENDIX A

PATIENT PARTICIPATION INFORMATION

Participant	Participation (chapter)	Age at Enucleation (months)	Eye Removed	Visual Acuity (in remaining eye)
ME01	II, III, IV, V, VI	18	Right	20/12.5
ME02	II, III, IV, V, VI	4	Right	20/12.5 +2
ME03	II, III, IV, V	24	Right	20/16 -1
ME04	II, III, IV, V, VI	60	Left	20/16
ME05	II, III, IV, V, VI	32	Left	20/32
ME06	II, III, IV, V	12	Right	20/16 -1
ME07	II, III, IV, V	18	Right	20/12.5
ME08	II, IV, V, VI	18	Left	20/12.5
ME09	V, VI	13	Left	20/16 -1
ME10	V, VI	17	Right	20/12.5 -1
ME11	V, VI	26	Right	20/12.5 +1
ME12	VI	13	Right	20/16 -1
ME13	VI	11	Left	20/20 -2

Table A1. Summary table indicating the studies each participant with one eye took part in, as well as, their corresponding enucleation and visual acuity information.

APPENDIX B

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FIGURE 1.1

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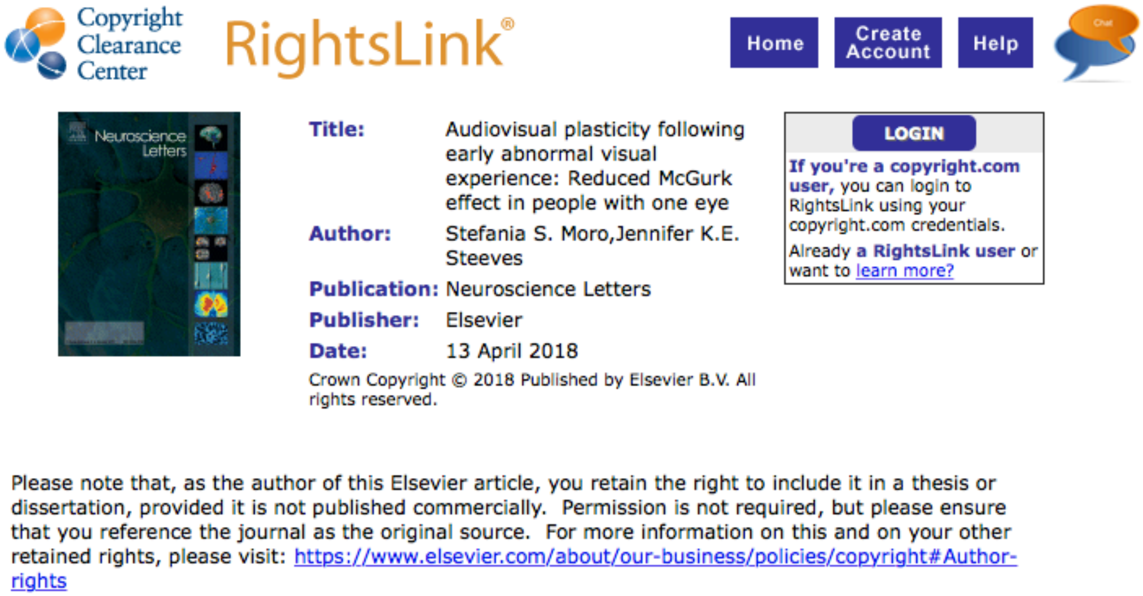
CHAPTER IV

AUDIOVISUAL PLASTICITY FOLLOWING EARLY ABNORMAL VISUAL EXPERIENCE: REDUCED MCGURK EFFECT IN PEOPLE WITH ONE EYE

Moro, S. S. & Steeves, J. K. E. (2018). Audiovisual Plasticity following early abnormal visual experience: Reduced McGurk Effect in people with one eye. *Neuroscience Letters.* DOI: 10.1016/j.neulet.2018.02.031.



Title: Audiovisual plasticity following early abnormal visual experience: Reduced McGurk effect in people with one eye

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CHAPTER V

SHORT AND LONG-TERM VISUAL DEPRIVATION LEADS TO ADAPTED USE OF AUDIOVISUAL INFORMATION FOR FACE-VOICE RECOGNITION

Moro, S. S., Hoover, A. E. N. & Steeves, J. K. E. (2018). Short and long-term visual deprivation leads to adapted use of audiovisual information for face-voice recognition. *Vision Research. DOI: 10.1016/j.visres.2018.01.009.*

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CHAPTER VI

EVIDENCE OF MULTISENSORY PLASTICITY: ASYMMETRICAL MEDIAL GENICULATE BODY IN PEOPLE WITH ONE EYE

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