The Influence of Interaural Asymmetries on Binaural Hearing Benefits in Adults with Cochlear Implants

By

Emily A. Burg

A dissertation submitted in partial fulfillment of
the requirements of the degree of

Doctor of Philosophy
(Communication Sciences and Disorders)

at the
UNIVERSITY OF WISCONSIN-MADISON
2022

Date of final oral examination: 5/4/2022

This dissertation has been approved by the following members of the Final Oral Committee:
Ruth Litovsky, Professor and Department Chair, Communication Sciences and Disorders
Philip Smith, Professor, Neuroscience
Sara Misurelli, Assistant Professor, Surgery
Viji Easwar, Assistant Professor, Communication Sciences and Disorders
Sriram Boothalingam, Assistant Professor, Communication Sciences and Disorders

THE INFLUENCE OF INTERAURAL ASYMMETRIES ON BINAURAL HEARING BENEFITS IN ADULTS WITH COCHLEAR IMPLANTS

Emily A. Burg

Under the supervision of Professor and Department Chair, Ruth Y. Litovsky

at the University of Wisconsin-Madison

Binaural hearing gives rise to important spatial hearing abilities, including sound localization and segregation of speech from noise. Individuals with severe-to-profound hearing loss in one ear who receive a unilateral cochlear implant (SSD-CI), and individuals with severe-to-profound hearing loss in both ears who receive bilateral cochlear implants (BiCIs) experience reduced benefits of binaural hearing compared to normal hearing (NH) listeners, making it difficult for many patients to communicate in the complex acoustic environments frequently encountered in daily life. However, the implications of hearing loss are not limited to behavioral performance. Successful communication requires mental resources, including engagement of attentional mechanisms and listening effort. Individuals with hearing loss frequently report elevated listening effort compared to individuals with normal hearing, which is associated with adverse outcomes including stress, fatigue, and social withdrawal. Therefore, it is imperative to investigate factors limiting binaural benefits and contributing to elevated listening effort in CI patients.

Binaural hearing relies on the successful integration of information across ears. Thus, interaural asymmetries in the delivery and encoding of information have the potential to limit binaural hearing abilities in CI patients. BiCI patients can experience interaural asymmetries due to pathological and surgical factors, and SSD-CI patients have inherent interaural asymmetry due to the difference in signal fidelity between acoustic and electric hearing. The overarching goal of this dissertation was to investigate the effect of across-ear asymmetries on binaural hearing outcomes in CI patients. The studies described in the subsequent chapters provide important insight into the amount of listening effort exerted by individuals with SSD and BiCIs in various listening conditions, elucidate potential mechanisms limiting binaural unmasking benefit in BiCI patients, and explore a novel avenue for the objective assessment of binaural fusion.

Table of Contents

DEDICATION

One, remember to look up at the stars and not down at your feet. Two, never give up work. Work gives you meaning and purpose and life is empty without it. Three, if you are lucky enough to find love, remember it is there and don't throw it away. — Stephen Hawking

To my loving and supportive parents, Louis and Linda Burg. Thank you for instilling the value of education in me at a young age, which undoubtedly led to my passion for school and science. Mom, you are my best friend, biggest role model, and the strongest woman I know. Thank you for introducing me to the field of auditory science, and for showing me that it is possible to have a successful career and be a wonderful mother, wife, and friend. Dad, you are the kindest, silliest, and most generous person I know. Thank you for showing me the value of hard work, being a constant rock for our family to lean on, and for reminding me to never take life too seriously.

To my hilarious, stubborn, and brilliant little brother, Adam (Billy) Burg. Thank you for making me laugh harder than anyone I've ever met, and for being the most loyal best friend I could ever ask for. I am so grateful for our close relationship, which has given me security and the confidence to know that we will be able to face anything that life throws at us, together. Finally, thank you for always reminding me that you're not hardcore, unless you live hardcore.

To my grandmothers in heaven, Nita Palm and Esther Pogachnik, you are both so special to me. Thank you for your endless love, for always believing in me, and for reminding me to live life to the fullest and follow my dreams.

To my amazing friends, thank you for countless unforgettable memories, for helping me move apartments almost every year of graduate school, and for always knowing what I need, even before I know it myself. Special thank you to my forever friends, Dakota Pawlak and Abigayle Peterson, for your unconditional support, and for showing me that friends can become family. I would be lost without you.

ACKNOWLEDGMENTS

Thank you to my wonderful mentor, Ruth Litovsky, for seeing a potential in me I was unaware of myself, for guiding me through the chaos and celebrating my growth, for being a noble example of research excellence and inclusion. Your unwavering support has given me the courage to set ambitious goals, trust in my capabilities, and continuously push myself to become a better scientist and person.

Thank you to the members of my dissertation committee: Philip Smith, Sara Misurelli, Sriram Boothalingam, and Viji Easwar, for your time, support, and mentorship. You have all had such a positive influence on my time in graduate school, and I am so grateful to have had the opportunity to learn from you.

Thank you to Tanvi Thakkar, for being the most supportive mentor and friend, and for teaching me how to do all the parts of science that they don't teach you in classes.

Thank you to Sara Misurelli, for recognizing my potential when I was just a silly undergrad, and encouraging me to constantly push myself outside of my comfort zone. I look up to you in so many ways and I am so grateful for your support over the past eight years. Your compassion, flexibility, and friendship sustained me through all of this.

Thank you to Shelly Godar, the glue that holds the BHSL together, for being the best lab manager, colleague, and friend, and thank you to all the other amazing lab members of the Binaural Hearing and Speech Lab who have given me so many wonderful memories and have helped me become the person I am today.

CHAPTER I. Introduction

Patients with severe-to-profound hearing loss who receive minimal benefit from hearing aids can re-gain access to sound via cochlear implants (CIs). CIs are implantable auditory prostheses that stimulate the auditory nerve with electrical pulses (Loizou, 1999). In the past, individuals with significant bilateral hearing loss received a CI in one ear, but subsequent work has demonstrated that one CI is typically not sufficient to restore the benefits of hearing with two ears, i.e., binaural hearing (e.g., Litovsky et al., 2004). Consequently, there has been a clinical impetus to promote use of bilateral cochlear implants (BiCIs) in an attempt to improve hearing abilities that rely on inputs from the two ears. Similarly, an increasing number of individuals who have one ear with normal or near-normal hearing and one with severe-to-profound sensorineural hearing loss, referred to as single-sided deafness (SSD), are now receiving a CI in their deaf ear in an attempt to improve spatial hearing abilities and reduce debilitating effects of tinnitus (Arndt et al., 2011; Buechner et al., 2010; Firszt, Holden, Reeder, Waltzman, & Arndt, 2012; Litovsky et al., 2019; Mertens, De Bodt, & Van de Heyning, 2016; Távora-Vieira, Rajan, Van De Heyning, & Mertens, 2019). Due to the importance of binaural benefits for listening in complex everyday environments, and the increasing prevalence of bilateral hearing in CI users, it is imperative to investigate the potential benefits that CI users may be able to access from bilateral stimulation. This chapter provides background on the anatomy and physiology of binaural processing, the importance of binaural hearing for making sense of an acoustic environment, and reviews the literature on binaural hearing abilities in individuals with normal hearing (NH) and individuals who use CIs. Additionally, this chapter discusses the multifaceted nature of communication, and the failuare of performance measures to adequately capture all aspects of listening. These concepts provide important context for the overarching goal of this dissertation and the specific aims described in each chapter.

I. Binaural Hearing

Binaural hearing refers to the auditory system's ability to integrate incoming signals from each ear. Binaural interactions enable listeners to group sounds into auditory objects, separate signals of interest from noise, and accurately identify the location of sound sources in an environment (for review, see Akeroyd, 2006). Two auditory cues enable sound localization in the horizontal plane- interaural time differences, and interaural level differences (for a review, see Middlebrooks & Green, 1991). Interaural time differences (ITDs) refer to the delay in time that it takes a low frequency sound (<1,500 Hz) to travel from the ear closest to the sound source to the opposite ear (Middlebrooks & Green, 1991; Rayleigh, 1907). These can also occur in low frequency envelope modulations of high frequency sounds (L. R. Bernstein, 2001; Middlebrooks & Green, 1991), and in transient sounds such as clicks (Middlebrooks & Green, 1991; Owrutsky, Benichoux, & Tollin, 2021; Yost, Wightman, & Green, 1971). Interaural level differences (ILDs) refer to a difference in level of high frequency sounds (>2,000 Hz) from the ear closest to the sound source compared to the ear farthest (Blauert & Butler, 1985). This level difference is caused by the physical barrier that the head creates (i.e., headshadow), which blocks sound waves, resulting in a decrease in intensity at the ear farthest from the sound source (Middlebrooks & Green, 1991).

The comparison of incoming signals from the two ears begins in the brainstem, where nuclei in the superior olivary complex analyze the frequency, intensity, and timing of auditory stimuli (Avan et al., 2015). The majority of central auditory neurons (at least 80%) receive information from both ears, and clusters of neurons are sensitive to level and timing characteristics of the incoming signal (for review of the anatomy and physiology of binarual hearing, see Moore, 1991). Neurons in the lateral superior olive (LSO) are sensitive to ILDs and encode intensity differences across ears by weighting excitatory glutamatergic input from the ipsilateral cochlear nucleus against inhibitory glycinergic input from the contralateral ear via the ipsilateral medial nucleus of the trapezoid body (for review, see Tollin, 2003). Greater stimulus intensity at the ipsilateral ear is encoded by a systematic increase in firing rate of LSO neurons (Tollin, Koka, & Tsai, 2008; Tsai, Koka, & Tollin, 2010). Neurons in the medial superior olive (MSO) are specialized in processing ITDs, primarily, low-frequency fine-structure ITDs, although some higher frequency MSO neurons are sensitive to ITDs in the temporal envelope as well (Yin & Chan, 1990). MSO neurons receive timing information via excitatory input from both ears (Young & Oertel, 2004). This temporal information is a result of peripheral neurons that characteristically fire at a particular phase of a periodic sound, meaning that they "phase-lock" to the fine structure of the signal. This timing information is sent to the MSO via an internal delay mechanism, which compensates for the physical delay between ears, or ITD (for review, see Owrutsky et al., 2021). When this information is passed to the MSO, the neurons that are specialized to that particular ITD will receive the input from each ear simultaneously, causing them to respond maximally (Yin & Chan, 1990). Thus, these neurons are known as "coincidence detectors." Historically, it has been thought that interaural level and timing information was processed individually by the LSO and MSO, respectively. However, recent evidence has shown that the LSO pathway exhibits anatomical and physiological specializations that facilitate the encoding of temporal information as well, and we now know that LSO neurons are sensitive to both ILDs and ITDs (Franken, Joris, & Smith, 2018; Joris & Trussell, 2018).

While ITDs and ILDs are the two acoustic cues that contribute to horizontal sound localization, a third binaural cue that is related to binaural fusion and affects the perceived width or diffuseness of a sound within the head is known as interaural correlation (IC). Binaural fusion refers to the perception of one unified sound when signals presented to each ear are correlated (Sayers & Cherry, 1957). When a NH listener is presented the same exact signal to both ears, it is perceived it as being fused (one sound) (Sayers & Cherry, 1957). As IC decreases, the perceived width of the sound increases, and at very low ICs the listener may perceive multiple sounds (Whitmer, Seeber, & Akeroyd, 2012). In the real world, continuously changing interaural cues can affect IC. When ITDs and ILDs change slowly over time, fusion is unaffected but the sound may be perceived as moving through space (Grantham, 1986; Grantham & Wightman, 1978). Rapid ITD and ILD fluctuations are unlikely to be produced by source movement, but can occur as a result of reflections from hard surfaces or reverberation in an acoustic space. The result of these more rapid fluctuations is a reduction in IC and an increase in perceived sound source width or diffuseness (Blauert & Lindemann, 1986).

In addition to improved sound localization, there are three benefits that contribute to speech understanding in noisy environments: the better ear effect (also known as the monaural head shadow effect), binaural unmasking or squelch, and binaural redundancy or summation. The better ear effect refers to the difference in signal-to-noise ratio (SNR) at each ear that occurs as a result of headshadow when target and noise are spatially separated. This benefit does not require binaural processing because listeners with access to two ears can simply attend to the ear with the better SNR (Zurek, 1993). Binaural unmasking and binaural summation, on the other hand, do necessitate binaural processing. Binaural unmasking refers to the auditory system’s ability to utilize binaural cues (i.e., ITDs and ILDs) to perceptually segregate two spatially separated sound sources (for review, see Avan et al., 2015). Binaural unmasking is particularly helpful in situations in which interferers are located on both sides of the head, and listeners are unable to utilize better-ear listening (Hawley, Litovsky, & Culling, 2004). Binaural summation refers to the benefit derived from obtaining duplicate copies of a sound, one from each ear, and an increase in perceptual loudness (Avan et al., 2015). Better ear listening and binaural unmasking contribute most significantly to the segregation of speech from noise in complex multi-talker environments (Hawley et al., 2004).

A. *Binaural Hearing in Adults with Normal Hearing*

NH individuals are able to make excellent use of binaural cues to accurately localize sounds and listen in noisy environments. Adults with NH are sensitive to ITDs as short as 15 µs and ILDs as small as 0.5 dB (Colburn, Shinn-Cunningham, Kidd, & Durlach, 2006; Durlach & Colburn, 1978). Similarly, they are extremely sensitive to deviations in IC, and are able to detect changes as small as 1 (perfectly correlated) to 0.96 (Colburn et al., 2006). Free-field localization studies with NH adults have shown that they are able utilize this exquisite sensitivity to binaural cues to localize sounds in the horizontal plane with errors as low as 5.6º (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007), as well as differentiate the location of two pure-tones that differ by only 1º (Mills, 1958). Studies investigating speech-in-noise performance in NH adults have shown that the amount of improvement derived from binaural hearing is dependent upon the type, number, and location of interferers relative to the target speech. For example, Hawley et al. (2004) found that, for a single interferer separated from the target by 60-90º, the better ear advantage was between 3-6 dB, the binaural unmasking advantage was between 2-4 dB, and neither of these benefits were significantly affected by interferer type (i.e., speech, reversed speech, modulated noise, noise). As the number of interferers was increased to three, better ear advantage was similar to that with one interferer, but binaural unmasking was as high as ~7dB, and was significantly affected by interferer type, with speech and reversed speech resulting in the largest amount of binaural unmasking (Hawley et al., 2004). Importantly, in conditions similar to real-world listening situations, with interferers located on both sides of the head, nearly all of the binaural advantage was attributable to binaural unmasking, with better ear listening providing little to no benefit (Hawley et al., 2004).

B. Binaural Hearing in Adults with Cochlear Implants

The only currently available intervention with the potential to restore binaural hearing in patients with bilateral or unilateral severe-to-profound sensorineural hearing loss are CIs. As such, bilateral implantation has become increasingly common with the goal of improving sound localization and speech understanding in noise in these patients. Similarly, individuals with SSD are now also being implanted in order to improve spatial hearing abilities and reduce debilitating effects of tinnitus (e.g., Arndt et al., 2011). Compared to hearing aids or unilateral implantation, most individuals with bilateral severe-to-profound hearing loss show improved sound localization (e.g., Gantz et al., 2002; Grantham et al., 2007; Laszig et al., 2004; Litovsky, Parkinson, & Arcaroli, 2009; Litovsky et al., 2004; Tyler, Dunn, Witt, & Noble, 2007; van Hoesel & Tyler, 2003) and speech understanding in noise (e.g., Gantz et al., 2002; Litovsky et al., 2004, 2006; Loizou et al., 2009; Schleich, Nopp, & D'Haese, 2004; Tyler et al., 2007; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel & Tyler, 2003) with BiCIs. This is also seen in individuals with SSD who are implanted with a CI (Arndt et al., 2011; J. G. W. Bernstein, Goupell, Schuchman, Rivera, & Brungart, 2016; J. G. W. Bernstein, Schuchman, & Rivera, 2017; Gartrell et al., 2014; Litovsky et al., 2019; Vermeire & Van De Heyning, 2009; Zeitler et al., 2015).

However, evidence suggests that CIs are not able to restore spatial hearing abilities to the level experienced by NH listeners. Kerber at el. (2012) compared sound localization root-mean-square (RMS) error between actual target location and localized angle for NH and BiCI listeners in quiet and found median RMS errors ranging from 14.8-44.8º for BiCI listeners, which was substantially larger than the RMS error range of 2.8-7.3º demonstrated by NH listeners. Jones et al. (2014) compared sound localization root-mean-square (RMS) error for NH listeners tested in an individualized virtual acoustic space (VAS) with unprocessed speech stimuli, NH listeners in VAS with speech stimuli processed with CI simulations, and BiCI listeners in free-field (FF) with pink noise bursts. They found that average RMS error was smallest for NH listeners in VAS with unprocessed stimuli (11.2º), followed by BiCI listeners in FF (27.9º), and finally NH listeners in VAS with CI simulations (34.2-40.6º) (Jones et al., 2014). Zeitler et al. (2015) compared FF sound localization RMS error of wideband noise stimuli for SSD-CI, BiCI, young NH, and older NH listeners, and found that average RMS errors were considerably smaller for the young and older NH groups (6.0º and 6.5º, respectively), compared to the BiCI (29.0º) and SSD-CI (30.0º) groups (Zeitler et al., 2015).

With regard to speech in noise performance, most of the bilateral benefit experienced by BiCI and SSD-CI listeners is due to better ear listening, with very little benefit attributable to true binaural processing (i.e., binaural unmasking, binaural redundancy) (e.g., Arndt et al., 2011; J. G. W. Bernstein et al., 2017; J. G. W. Bernstein, Stakhovskaya, Jensen, & Goupell, 2020; Gantz et al., 2002; Goupell et al., 2016; Goupell, Stakhovskaya, & Bernstein, 2018; Litovsky et al., 2009, 2006; Loizou et al., 2009; Schleich et al., 2004; van Hoesel et al., 2002; van Hoesel & Tyler, 2003; Vermeire & Van De Heyning, 2009). Consistent with this finding, several studies have demonstrated reduced binaural unmasking benefit in CI users compared to NH listeners (e.g., J. G. W. Bernstein et al., 2016, 2017, 2020; Goupell et al., 2016, 2018; Litovsky et al., 2006; Loizou et al., 2009; Schleich et al., 2004). However, a recent study by Bernstein and colleagues (2016) used a contralateral unmasking paradigm in which the target was presented to the better ear and the masker was presented ipsilaterally or diotically. Binaural unmasking was calculated as the difference in speech intelligibility between ipsilateral and diotic masker presentation. Results showed that some BiCI and SSD-CI listeners can obtain a binaural unmasking advantage of up to 4-5 dB, which is on par with that observed in NH listeners in the FF (J. G. W. Bernstein et al., 2016; Hawley et al., 2004). Goupell et al. (2018) conducted a follow-up study in BiCI listeners with asymmetric hearing histories or early onset of deafness. Instead of binaural unmasking, they found that these listeners demonstrated interference, defined as a decrement in performance when listening with two ears versus one (Goupell et al., 2018). In five out of nine listeners, interference occurred regardless of whether the target was presented to the better ear or poorer ear. Additionally, the magnitude of interference was negatively correlated with speech intelligibility in the target ear, and positively correlated with duration of deafness of the target ear and speech intelligibility of the contralateral ear (Goupell et al., 2018). A subsequent study in SSD-CI listeners, in which the target was presented to the better ear or the poorer ear, found that the outcome was highly dependent upon which ear was being attended to. SSD-CI listeners showed interference when the target was presented to the CI ear, and binaural unmasking when the target was presented to the acoustic ear. Interestingly, the magnitude of interference was not related to speech intelligibility of the CI ear, but was significantly correlated with listener age (J. G. W. Bernstein et al., 2020).

II. Interaural Asymmetry in Adults with Cochlear Implants

The majority of CI users with hearing in both ears demonstrate interaural asymmetries to some degree. BiCI listeners can experience asymmetries due to pathological, surgical, and device related factors (for review, see Kan & Litovsky, 2015). Pathological asymmetries include etiology of hearing loss, degree of hearing loss, age at onset of deafness, duration of deafness, and differential degeneration of peripheral and central processes (Coco et al., 2007; Leake, Hradek, & Snyder, 1999; Litovsky et al., 2012). Surgical induced asymmetries include trauma to the inner ear during surgery and differences in electrode array insertion which can cause interaural place-of-stimulation mismatch and differential spread of electrical current across ears (Arenberg Bierer, 2010; Fayad, Makarem, & Linthicum, 2009; Kan & Litovsky, 2015; Li, Somdas, Eddington, & Nadol, 2007; Litovsky et al., 2012; Somdas, Li, Whiten, Eddington, & Nadol, 2007; van Hoesel, 2004). Device related asymmetries result from the two processors working independently without obligatory coordination; thus, binaural cues that convey precise timing and level differences across ears are not captured or presented to the auditory system with fidelity (Kan & Litovsky, 2015; Litovsky et al., 2012; van Hoesel, 2004). Surgical and pathological factors affect how intracochlear electrodes stimulate neural populations (i.e., the electrode-neuron interface) (Arenberg Bierer, 2010). Arenberg Bierer (2010) investigated the electrode-neuron interface in BiCI listeners using focused electrode stimulation, and found that electrode channels with high focused stimulation thresholds had poor spectral resolution and smaller dynamic range (DR). Small DR is related to steep loudness growth functions, and both of these have been associated with poor speech perception abilities (Arenberg Bierer, 2010; Fu & Shannon, 2000; Loizou, Dorman, & Fitzke, 2000). Thus, the electrode-neuron interface can vary within an ear, potentially degrading monaural performance, as well as across ears, contributing to interaural asymmetries in BiCI users.

SSD-CI listeners also experience significant interaural asymmetry due to the disparate hearing modalities in each ear (i.e., acoustic in one, electric in the other). In addition to asymmetries caused by pathology to the deaf ear, there are also asymmetries in spectral and temporal characteristics across ears. While CIs can have up to 22 individual electrodes on an array, only 8-10 are stimulated at a given time, resulting in a representation of the sound that is spectrally degraded compared to the acoustic ear. Further, available electrode arrays only extend about 1.5 turns into the cochlea, requiring frequency information to be compressed into the smaller area stimulated by the CI (for review, see Aronoff, Shayman, Prasad, Suneel, & Stelmach, 2015). Additionally, there are temporal differences in stimulation due to the traveling wave delay in the acoustic ear, which will stimulate high frequencies before low frequencies, while the CI will stimulate all frequencies simultaneously (Aronoff et al., 2015). Because onset cues are important for auditory grouping, this temporal mismatch may affect binaural fusion in SSD-CI listeners (Aronoff et al., 2015; Brown, Stecker, & Tollin, 2015).

Much of the evidence on binaural hearing with asymmetric ears has focused mainly on whether limitations in the poorer ear create a “bottleneck” for binaural benefit. For example, previous work using single binaural pairs of electrodes has shown that sensitivity to binaural cues in BiCI adults is limited by the ear with poorer sensitivity to temporal information (Anderson, Kan, & Litovsky, 2019; Ihlefeld, Carlyon, Kan, Churchill, & Litovsky, 2015). Behavioral studies have shown that the amount of binaural unmasking experienced by BiCI adults is dependent upon which ear they are attending to. Listeners experience a binaural advantage when attending to the better ear, and interference when attending to the poorer ear, and the amount of interference is negatively related to speech intelligibility of the target ear, and positively correlated with duration of deafness of target ear and speech intelligibility of the contralateral ear (J. G. W. Bernstein et al., 2016; Goupell et al., 2018). While poorer-ear performance is certainly an important factor affecting binaural outcomes in CI users, it is also likely that the *degree* of interaural asymmetry affects binaural processing. When patients subjectively rated the impact of their hearing sensitivity and interaural asymmetry on their perceived hearing disability, results showed that asymmetry played a significant role for spatial hearing, sound naturalness and clarity, signal segregation, and effort of conversation dimensions, independent of hearing sensitivity (Gatehouse & Noble, 2004).

The importance of interaural asymmetry is also supported by experiments investigating brain plasticity in patients with asymmetric hearing. For instance, studies have found evidence of cortical reorganization that suggests a strong preference for the better ear in children with bilateral hearing loss who were unilaterally implanted, and in children with SSD (Gordon, Wong, & Papsin, 2013; Lee et al., 2020; Polonenko, Gordon, Cushing, & Papsin, 2017). Some studies have also found similar effects in adults who had NH and then experienced SSD later in life (Bilecen et al., 2000; Burton, Firszt, Holden, Agato, & Uchanski, 2012; Hanss et al., 2009; Khosla et al., 2003; Ponton et al., 2001). Studies in animals with SSD and in children with SSD have shown that reorganization in favor of one ear is maladaptive for binaural hearing outcomes (for review, see K. Gordon & Kral, 2019). Due to the high prevalence of interaural asymmetry in CI patients, more work is needed to elucidate how different types of asymmetry affect binaural outcomes in BiCI and SSD-CI users.

III. Listening Effort and Pupillometry

Human communication is a complicated, multifaceted process which cannot be fully understood by a single performance measure such as a speech intelligibility score. Numerous peripheral and central processes contribute to verbal communication, including the ability to attend to and accurately encode the speech signal, process and comprehend what was said which can include filling in missed information, and formulating a response. The deliberate allocation of attention-related cognitive resources to perform a difficult listening task is known as *listening effort* (Pichora-Fuller et al., 2016). A participant's engagement or motivation to perform the task is also thought to contribute to the amount of effort they expend (Winn, Wendt, Koelewijn, & Kuchinsky, 2018). Consequently, individuals with the same intelligibility score may exert different amounts of listening effort due to individual factors, such as hearing or cognitive abilities (Ohlenforst et al., 2017; Zekveld, Kramer, & Festen, 2011). In ideal listening situations such as quiet rooms, communication can be relatively effortless, however, in more complex environments such as noisy restaurants, communication can be extremely taxing and may require increased top-down processing to compensate for suboptimal input (Başkent et al., 2016; Downs & Crum, 1978; Mattys, Davis, Bradlow, & Scott, 2012; Rönnberg, 2003; Wild et al., 2012). This is especially true for listeners with hearing impairment, who must overcome the additional signal degradation caused by their hearing loss and assistive listening technology. In fact, individuals with hearing loss generally report being more fatigued after an hour of listening, and find listening in noisy environments to be more cognitively taxing than NH listeners (Edwards, 2007; Zekveld, Kramer, & Festen, 2010). Additionally, individuals with CIs show less release from effort than NH listeners when sentences are semantically logical compared to when they are not (Winn, 2016). A study by Gatehouse and Noble (2004) measured a range of hearing disabilities using a subjective questionnaire (Speech, Spatial and Qualities of Hearing Scale) and found that hearing impaired patients reported the greatest disability for the following sections: listening with simultaneous talkers, ease of listening, listening in noisy settings and groups, and perceiving sound movement or distance. Additionally, they compared these measures with an independent measure of handicap, and found that sound identification, attention, spatial hearing, and listening effort difficulties strongly contributed to the hearing disability-handicap relationship, but speech intelligibility did not, indicating that it is important to examine listening effort even in the absence of speech perception difficulties (Gatehouse & Noble, 2004). The clinical relevance of listening effort is further supported by evidence suggesting that elevated effort has negative psycho-social consequences, including stress, emotional strain, fatigue, and withdrawal from social situations, highlighting the significant impact that listening effort can have on quality of life (Alhanbali, Dawes, Lloyd, & Munro, 2018; Alhanbali, Dawes, Millman, & Munro, 2019; Hétu, Riverin, Lalande, Getty, & St-Cyr, 1988; Hughes, Hutchings, Rapport, McMahon, & Boisvert, 2018; Stephens & Hétu, 1991).

Numerous subjective, behavioral, and physiological methods have been used to quantify listening effort (McGarrigle et al., 2014). An increasingly popular technique is known as pupillometry, or the measure of pupil dilation. Unlike other physiological measures that are susceptible to electrical and magnetic artifacts such as functional magnetic resonance imaging and electroencephalography, pupillometry is compatible with amplification devices (e.g., hearing aids) and implantable devices (e.g., cochlear implants) (Friesen & Picton, 2010; Gilley et al., 2006; Wagner, Nagels, Toffanin, Opie, & Başkent, 2019). Additionally, pupillometry is comparatively fast and affordable, giving it the potential to be utilized in research and the audiology clinic (Winn et al., 2018). Pupillometry also has the advantage of tracking changes in pupil dilation as they unfold over time, enabling the examination of effort at different stages of communication (e.g., listening to a sentence, processing what was heard, repeating the sentence back, repairing missed information, etc.) (Winn et al., 2018).

IV. References

Akeroyd, M. A. (2006). The psychoacoustics of binaural hearing. *International Journal of Audiology*. https://doi.org/10.1080/14992020600782626

Alhanbali, S., Dawes, P., Lloyd, S., & Munro, K. J. (2018). Hearing Handicap and Speech Recognition Correlate With Self-Reported Listening Effort and Fatigue. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000515

Alhanbali, S., Dawes, P., Millman, R. E., & Munro, K. J. (2019). Measures of Listening Effort Are Multidimensional. *Ear and Hearing*, *40*(5), 1084–1097. https://doi.org/10.1097/AUD.0000000000000697

Anderson, S. R., Kan, A., & Litovsky, R. Y. (2019). Asymmetric temporal envelope encoding: Implications for within- and across-ear envelope comparison. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.5121423

Arenberg Bierer, J. (2010). Probing the Electrode-Neuron Interface With Focused Cochlear Implant Stimulation. *Trends in Amplification*. https://doi.org/10.1177/1084713810375249

Arndt, S., Aschendorff, A., Laszig, R., Beck, R., Schild, C., Kroeger, S., … Wesarg, T. (2011). Comparison of pseudobinaural hearing to real binaural hearing rehabilitation after cochlear implantation in patients with unilateral deafness and tinnitus. *Otology and Neurotology*, *32*(1), 39–47. https://doi.org/10.1097/MAO.0b013e3181fcf271

Aronoff, J. M., Shayman, C. S., Prasad, A., Suneel, D., & Stelmach, J. (2015). Unilateral spectral and temporal compression reduces binaural fusion for normal hearing listeners with cochlear implant simulations. *Hearing Research*. https://doi.org/10.1016/j.heares.2014.12.005

Avan, P., Giraudet, F., & Büki, B. (2015). Importance of binaural hearing. *Audiology and Neurotology*. https://doi.org/10.1159/000380741

Başkent, D., Clarke, J., Pals, C., Benard, M. R., Bhargava, P., Saija, J., … Gaudrain, E. (2016). Cognitive Compensation of Speech Perception With Hearing Impairment, Cochlear Implants, and Aging: How and to What Degree Can It Be Achieved? *Trends in Hearing*. https://doi.org/10.1177/2331216516670279

Bernstein, J. G. W., Goupell, M. J., Schuchman, G. I., Rivera, A. L., & Brungart, D. S. (2016). Having two ears facilitates the perceptual separation of concurrent talkers for bilateral and single-sided deaf cochlear implantees. *Ear and Hearing*, *37*(3), 289–302. https://doi.org/10.1097/AUD.0000000000000284

Bernstein, J. G. W., Schuchman, G. I., & Rivera, A. L. (2017). Head shadow and binaural squelch for unilaterally deaf cochlear implantees. *Otology and Neurotology*. https://doi.org/10.1097/MAO.0000000000001469

Bernstein, J. G. W., Stakhovskaya, O. A., Jensen, K. K., & Goupell, M. J. (2020). Acoustic Hearing Can Interfere with Single-Sided Deafness Cochlear-Implant Speech Perception. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000805

Bernstein, L. R. (2001). Auditory processing of interaural timing information: New insights. *Journal of Neuroscience Research*. https://doi.org/10.1002/jnr.10103.abs

Bilecen, D., Seifritz, E., Radü, E. W., Schmid, N., Wetzel, S., Probst, R., & Scheffler, K. (2000). Cortical reorganization after acute unilateral hearing loss traced by fMRI. *Neurology*. https://doi.org/10.1212/wnl.54.3.765

Blauert, J., & Butler, R. A. (1985). Spatial Hearing: The Psychophysics of Human Sound Localization by Jens Blauert . *The Journal of the Acoustical Society of America*.

https://doi.org/10.1121/1.392109

Blauert, J., & Lindemann, W. (1986). Spatial mapping of intracranial auditory events for various degrees of interaural coherence. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.393471

Brown, A. D., Stecker, G. C., & Tollin, D. J. (2015). The Precedence Effect in Sound Localization. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-014-0496-2

Buechner, A., Brendel, M., Lesinski-Schiedat, A., Wenzel, G., Frohne-Buechner, C., Jaeger, B., & Lenarz, T. (2010). Cochlear implantation in unilateral deaf subjects associated with ipsilateral tinnitus. *Otology and Neurotology*, *31*(9), 1381–1385. https://doi.org/10.1097/MAO.0b013e3181e3d353

Burton, H., Firszt, J. B., Holden, T. A., Agato, A., & Uchanski, R. M. (2012). Activation lateralization in human core, belt, and parabelt auditory fields with unilateral deafness compared to normal hearing. *Brain Research*. https://doi.org/10.1016/j.brainres.2012.02.066

Coco, A., Epp, S. B., Fallon, J. B., Xu, J., Millard, R. E., & Shepherd, R. K. (2007). Does cochlear implantation and electrical stimulation affect residual hair cells and spiral ganglion neurons? *Hearing Research*. https://doi.org/10.1016/j.heares.2006.12.004

Colburn, H. S., Shinn-Cunningham, B. G., Kidd, G., & Durlach, N. I. (2006). The perceptual consequences of binaural hearing. *International Journal of Audiology*. https://doi.org/10.1080/14992020600782642

Downs, D. W., & Crum, M. A. (1978). Processsing demands during auditory learning under degraded listening conditions. *Journal of Speech and Hearing Research*. https://doi.org/10.1044/jshr.2104.702

Durlach, N. I., & Colburn, H. S. (1978). Binaural Phenomena. In *Hearing*. https://doi.org/10.1016/b978-0-12-161904-6.50017-8

Edwards, B. (2007). The Future of Hearing Aid Technology. *Trends in Amplification*, *11*(1), 31–45. https://doi.org/10.1177/1084713806298004

Fayad, J. N., Makarem, A. O., & Linthicum, F. H. (2009). Histopathologic assessment of fibrosis and new bone formation in implanted human temporal bones using 3D reconstruction. *Otolaryngology - Head and Neck Surgery*. https://doi.org/10.1016/j.otohns.2009.03.031

Firszt, J. B., Holden, L. K., Reeder, R. M., Waltzman, S. B., & Arndt, S. (2012). Auditory abilities after cochlear implantation in adults with unilateral deafness: a pilot study. *Otology & Neurotology : Official Publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, *33*(8), 1339–1346. https://doi.org/10.1097/MAO.0b013e318268d52d

Franken, T. P., Joris, P. X., & Smith, P. H. (2018). Principal cells of the brainstem's interaural sound level detector are temporal differentiators rather than integrators. *ELife*. https://doi.org/10.7554/eLife.33854

Friesen, L. M., & Picton, T. W. (2010). A method for removing cochlear implant artifact. *Hearing Research*, *259*(1–2), 95–106. https://doi.org/10.1016/j.heares.2009.10.012

Fu, Q.-J., & Shannon, R. V. (2000). Effects of dynamic range and amplitude mapping on phoneme recognition in nucleus-22 cochlear implant users. *Ear and Hearing*. https://doi.org/10.1097/00003446-200006000-00006

Gantz, B. J., Tyler, R. S., Rubinstein, J. T., Wolaver, A., Lowder, M., Abbas, P., … Preece, J. P. (2002). Binaural cochlear implants placed during the same operation. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200203000-00012

Gartrell, B. C., Jones, H. G., Kan, A., Buhr-Lawler, M., Gubbels, S. P., & Litovsky, R. Y. (2014). Investigating long-term effects of cochlear implantation in single-sided deafness: A best practice model for longitudinal assessment of spatial hearing abilities and tinnitus handicap. *Otology and Neurotology*, *35*(9), 1525–1532. https://doi.org/10.1097/MAO.0000000000000437

Gatehouse, S., & Noble, W. G. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *International Journal of Audiology*, *43*(2), 85–99. https://doi.org/10.1080/14992020400050014

Gilley, P. M., Sharma, A., Dorman, M. F., Finley, C. C., Panch, A. S., & Martin, K. (2006). Minimization of cochlear implant stimulus artifact in cortical auditory evoked potentials. *Clinical Neurophysiology*, *117*(8), 1772–1782. https://doi.org/10.1016/j.clinph.2006.04.018

Gordon, K. A., & Kral, A. (2019). Animal and human studies on developmental monaural hearing loss. *Hearing Research*. https://doi.org/10.1016/j.heares.2019.05.011

Gordon, K. A., Wong, D. D. E., & Papsin, B. C. (2013). Bilateral input protects the cortex from unilaterally-driven reorganization in children who are deaf. *Brain*. https://doi.org/10.1093/brain/awt052

Goupell, M. J., Kan, A., & Litovsky, R. Y. (2016). Spatial attention in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*, *140*(3), 1652–1662. https://doi.org/10.1121/1.4962378

Goupell, M. J., Stakhovskaya, O. A., & Bernstein, J. G. W. (2018). Contralateral Interference Caused by Binaurally Presented Competing Speech in Adult Bilateral Cochlear-Implant Users. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000470

Grantham, D. W. (1986). Detection and discrimination of simulated motion of auditory targets in the horizontal plane. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.393201

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Labadie, R. F., & Haynes, D. S. (2007). Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31806dc21a

Grantham, D. W., & Wightman, F. L. (1978). Detectability of varying interaural temporal differences. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.381751

Hanss, J., Veuillet, E., Adjout, K., Besle, J., Collet, L., & Thai-Van, H. (2009). The effect of long-term unilateral deafness on the activation pattern in the auditory cortices of French-native speakers: Influence of deafness side. *BMC Neuroscience*. https://doi.org/10.1186/1471-2202-10-23

Hawley, M. L., Litovsky, R. Y., & Culling, J. F. (2004). The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *The Journal of the Acoustical Society of America*, *115*(2), 833–843. https://doi.org/10.1121/1.1639908

Hétu, R., Riverin, L., Lalande, N., Getty, L., & St-Cyr, C. (1988). Qualitative analysis of the handicap associated with occupational hearing loss. *British Journal of Audiology*. https://doi.org/10.3109/03005368809076462

Hughes, S. E., Hutchings, H. A., Rapport, F. L., McMahon, C. M., & Boisvert, I. (2018). Social connectedness and perceived listening effort in adult cochlear implant users: A grounded theory to establish content validity for a new patient-reported outcome measure. *Ear and Hearing*, *39*(5), 922–934. https://doi.org/10.1097/AUD.0000000000000553

Ihlefeld, A., Carlyon, R. P., Kan, A., Churchill, T. H., & Litovsky, R. Y. (2015). Limitations on

Monaural and Binaural Temporal Processing in Bilateral Cochlear Implant Listeners. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-015-0527-7

Jones, H. G., Kan, A., & Litovsky, R. Y. (2014). Comparing sound localization deficits in bilateral cochlear-implant users and vocoder simulations with normal-hearing listeners. *Trends in Hearing*. https://doi.org/10.1177/2331216514554574

Joris, P. X., & Trussell, L. O. (2018). The Calyx of Held: A Hypothesis on the Need for Reliable Timing in an Intensity-Difference Encoder. *Neuron*. https://doi.org/10.1016/j.neuron.2018.10.026

Kan, A., & Litovsky, R. Y. (2015). Binaural hearing with electrical stimulation. *Hearing Research*. https://doi.org/10.1016/j.heares.2014.08.005

Kerber, S., & Seeber, B. U. (2012). Sound localization in noise by normal-hearing listeners and cochlear implant users. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e318257607b

Khosla, D., Ponton, C. W., Eggermont, J. J., Kwong, B., Don, M., & Vasama, J. P. (2003). Differential ear effects of profound unilateral deafness on the adult human central auditory system. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-002-3014-x

Laszig, R., Aschendorff, A., Stecker, M., Müller-Deile, J., Maune, S., Dillier, N., … Doering, W. (2004). Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-Month postoperative results. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200411000-00016

Leake, P. A., Hradek, G. T., & Snyder, R. L. (1999). Chronic electrical stimulation by a cochlear implant promotes survival of spiral ganglion neurons after neonatal deafness. *Journal of Comparative Neurology*. https://doi.org/10.1002/(SICI)1096-9861(19991004)412:4<543::AID-CNE1>3.0.CO;2-3

Lee, H. J., Smieja, D., Polonenko, M. J., Cushing, S. L., Papsin, B. C., & Gordon, K. A. (2020). Consistent and chronic cochlear implant use partially reverses cortical effects of single sided deafness in children. *Scientific Reports*. https://doi.org/10.1038/s41598-020-78371-6

Li, P. M. M. C., Somdas, M. A., Eddington, D. K., & Nadol, J. B. (2007). Analysis of intracochlear new bone and fibrous tissue formation in human subjects with cochlear implants. *Annals of Otology, Rhinology and Laryngology*. https://doi.org/10.1177/000348940711601004

Litovsky, R. Y., Goupell, M. J., Godar, S., Grieco-Calub, T., Jones, G. L., Garadat, S. N., … Misurelli, S. M. (2012). Studies on bilateral cochlear implants at the University of Wisconsin's binaural hearing and speech laboratory. *Journal of the American Academy of Audiology*. https://doi.org/10.3766/jaaa.23.6.9

Litovsky, R. Y., Moua, K., Godar, S., Kan, A., Misurelli, S. M., & Lee, D. J. (2019). Restoration of spatial hearing in adult cochlear implant users with single-sided deafness. *Hearing Research*, *372*, 69–79. https://doi.org/10.1016/j.heares.2018.04.004

Litovsky, R. Y., Parkinson, A., & Arcaroli, J. (2009). Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*, *30*(4), 419–431. https://doi.org/10.1097/AUD.0b013e3181a165be

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., & Yu, G. (2004). Bilateral Cochlear Implants in Adults and Children. *Archives of Otolaryngology - Head and Neck Surgery*, *130*(5), 648–655. https://doi.org/10.1001/archotol.130.5.648

Litovsky, R. Y., Parkinson, A., Arcaroli, J., & Sammeth, C. (2006). Simultaneous Bilateral

Cochlear Implantation in Adults: A multicenter clinical study. *Ear and Hearing*, *27*(6), 714–731. https://doi.org/10.1097/01.aud.0000246816.50820.42.Simultaneous

Loizou, P. C. (1999). Introduction to cochlear implants. *IEEE Engineering in Medicine and Biology Magazine*. https://doi.org/10.1109/51.740962

Loizou, P. C., Dorman, M. F., & Fitzke, J. (2000). The effect of reduced dynamic range on speech understanding: Implications for patients with cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/00003446-200002000-00006

Loizou, P. C., Hu, Y., Litovsky, R. Y., Yu, G., Peters, R., Lake, J., & Roland, P. (2009). Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3036175

Mattys, S. L., Davis, M. H., Bradlow, A. R., & Scott, S. K. (2012). Speech recognition in adverse conditions: A review. *Language and Cognitive Processes*. https://doi.org/10.1080/01690965.2012.705006

McGarrigle, R., Munro, K. J., Dawes, P., Stewart, A. J., Moore, D. R., Barry, J. G., & Amitay, S. (2014). Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group “white paper.” *International Journal of Audiology*, Vol. 53, pp. 433–445. https://doi.org/10.3109/14992027.2014.890296

Mertens, G., De Bodt, M., & Van de Heyning, P. (2016). Cochlear implantation as a long-term treatment for ipsilateral incapacitating tinnitus in subjects with unilateral hearing loss up to 10 years. *Hearing Research, 331*, 1–6. https://doi.org/10.1016/j.heares.2015.09.016

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology*. https://doi.org/10.1146/annurev.ps.42.020191.001031

Mills, A. W. (1958). On the Minimum Audible Angle. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1909553

Moore, D. R. (1991). Anatomy and physiology of binaural hearing. *International Journal of Audiology*. https://doi.org/10.3109/00206099109072878

Ohlenforst, B., Zekveld, A. A., Lunner, T., Wendt, D., Naylor, G., Wang, Y., … Kramer, S. E. (2017). Impact of stimulus-related factors and hearing impairment on listening effort as indicated by pupil dilation. *Hearing Research, 351*, 68–79. https://doi.org/10.1016/j.heares.2017.05.012

Owrutsky, Z., Benichoux, V., & Tollin, D. J. (2021). Binaural Hearing by the Mammalian Auditory Brainstem: Joint Coding. In R. Y. Litovsky, M. J. Goupell, R. R. Fay, & A. N. Popper (Eds.), *Binaural Hearing* (pp. 113–144).

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., … Wingfield, A. (2016). Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL). *Ear and Hearing, 37*, 5S-27S. https://doi.org/10.1097/AUD.0000000000000312

Polonenko, M. J., Gordon, K. A., Cushing, S. L., & Papsin, B. C. (2017). Cortical organization restored by cochlear implantation in young children with single sided deafness. *Scientific Reports*. https://doi.org/10.1038/s41598-017-17129-z

Ponton, C. W., Vasama, J. P., Tremblay, K. L., Khosla, D., Kwong, B., & Don, M. (2001). Plasticity in the adult human central auditory system: evidence from late-onset profound unilateral deafness. *Hearing Research*. https://doi.org/10.1016/S0378-5955(01)00214-3

Rayleigh, Lord. (1907). XII. On our perception of sound direction . *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*. https://doi.org/10.1080/14786440709463595

Rönnberg, J. (2003). Cognition in the hearing impaired and deaf as a bridge between signal and dialogue: A framework and a model. *International Journal of Audiology*. https://doi.org/10.3109/14992020309074626

Sayers, B. M., & Cherry, E. C. (1957). Mechanism of Binaural Fusion in the Hearing of Speech. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1914990

Schleich, P., Nopp, P., & D’Haese, P. (2004). Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000130792.43315.97

Somdas, M. A., Li, P. M. M. C., Whiten, D. M., Eddington, D. K., & Nadol, J. B. (2007). Quantitative evaluation of new bone and fibrous tissue in the cochlea following cochlear implantation in the human. *Audiology and Neurotology*. https://doi.org/10.1159/000103208

Stephens, D., & Hétu, R. (1991). Impairment, disability and handicap in audiology: Towards a consensus. *International Journal of Audiology*, Vol. 30, pp. 185–200. https://doi.org/10.3109/00206099109072885

Távora-Vieira, D., Rajan, G. P., Van De Heyning, P., & Mertens, G. (2019). Evaluating the Long-Term Hearing Outcomes of Cochlear Implant Users with Single-Sided Deafness. *Otology and Neurotology*, *40*(6), E575–E580. https://doi.org/10.1097/MAO.0000000000002235

Tollin, D. J. (2003). The lateral superior olive: A functional role in sound source localization. *Neuroscientist*. https://doi.org/10.1177/1073858403252228

Tollin, D. J., Koka, K., & Tsai, J. J. (2008). Interaural level difference discrimination thresholds for single neurons in the lateral superior olive. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.5421-07.2008

Tsai, J. J., Koka, K., & Tollin, D. J. (2010). Varying overall sound intensity to the two ears impacts interaural level difference discrimination thresholds by single neurons in the lateral superior olive. *Journal of Neurophysiology*. https://doi.org/10.1152/jn.00911.2009

Tyler, R. S., Dunn, C. C., Witt, S. A., & Noble, W. G. (2007). Speech perception and localization with adults with bilateral sequential cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31803153e2

van Hoesel, R. (2004). Exploring the benefits of bilateral cochlear implants. *Audiology and Neuro-Otology*. https://doi.org/10.1159/000078393

van Hoesel, R., Ramsden, R., & O’Driscoll, M. (2002). Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. *Ear and Hearing*. https://doi.org/10.1097/00003446-200204000-00006

van Hoesel, R., & Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1539520

Vermeire, K., & Van De Heyning, P. (2009). Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiology and Neurotology*, *14*(3), 163–171. https://doi.org/10.1159/000171478

Wagner, A. E., Nagels, L., Toffanin, P., Opie, J. M., & Başkent, D. (2019). Individual Variations in Effort: Assessing Pupillometry for the Hearing Impaired. *Trends in Hearing*, *23*. https://doi.org/10.1177/2331216519845596

Whitmer, W. M., Seeber, B. U., & Akeroyd, M. A. (2012). Apparent auditory source width insensitivity in older hearing-impaired individuals. *The Journal of the Acoustical Society of*

America. https://doi.org/10.1121/1.4728200

Wild, C. J., Yusuf, A., Wilson, D. E., Peelle, J. E., Davis, M. H., & Johnsrude, I. S. (2012). Effortful listening: The processing of degraded speech depends critically on attention. *Journal of Neuroscience*, *32*(40), 14010–14021. https://doi.org/10.1523/JNEUROSCI.1528-12.2012

Winn, M. B. (2016). Rapid Release From Listening Effort Resulting From Semantic Context, and Effects of Spectral Degradation and Cochlear Implants. *Trends in Hearing*. https://doi.org/10.1177/2331216516669723

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best Practices and Advice for Using Pupillometry to Measure Listening Effort: An Introduction for Those Who Want to Get Started. *Trends in Hearing*, Vol. 22. https://doi.org/10.1177/2331216518800869

Yin, T. C. T., & Chan, J. C. K. (1990). Interaural time sensitivity in medial superior olive of cat. *Journal of Neurophysiology*. https://doi.org/10.1152/jn.1990.64.2.465

Yost, W. A., Wightman, F. L., & Green, D. M. (1971). Lateralization of Filtered Clicks. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1912806

Young, E., & Oertel, D. (2004). Cochlear Nucleus. In G. M. Shepherd (Ed.), *The Synaptic Organization of the Brain* (pp. 125–163). https://doi.org/10.1093/acprof:oso/9780195159561.001.1

Zeitler, D. M., Dorman, M. F., Natale, S. J., Loiselle, L. M., Yost, W. A., & Gifford, R. H. (2015). Sound source localization and speech understanding in complex listening environments by single-sided deaf listeners after cochlear implantation. *Otology and Neurotology*, *36*(9), 1467–1471. https://doi.org/10.1097/MAO.0000000000000841

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2010). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. *Ear and Hearing*, *31*(4), 480–490. https://doi.org/10.1097/AUD.0b013e3181d4f251

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2011). Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. *Ear & Hearing*, *32*(4), 498–510. https://doi.org/10.1097/AUD.0b013e31820512bb

Zurek, P. (1993). Binaural advantages and directional effects in speech intelligibility. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical Factors Affecting Hearing Aid Performance*.

CHAPTER II. Systematic Comparison of Trial Exclusion Criteria for Pupillometry Data Analysis in Individuals with Single-Sided Deafness and Normal Hearing (*published in Trends in Hearing, 25, 23312165211013256)

I. Abstract

The measurement of pupil dilation has become a common way to assess listening effort. Pupillometry data are subject to artifacts, requiring highly contaminated data to be discarded from analysis. It is unknown how trial exclusion criteria impact experimental results. The present study examined the effect of a common exclusion criterion, percentage of blinks, on speech intelligibility and pupil dilation measures in 9 participants with single sided deafness (SSD) and 20 participants with normal hearing. Participants listened to and repeated sentences in quiet or with speech maskers. Pupillometry trials were processed using three levels of blink exclusion criteria: 15%, 30%, and 45%. These percentages reflect a threshold for missing data points in a trial, where trials that exceed the threshold are excluded from analysis. Results indicated that pupil dilation was significantly greater and intelligibility was significantly lower in the masker compared with the quiet condition for both groups. Across group comparisons revealed that speech intelligibility in the SSD group decreased significantly more than the normal hearing group from quiet to masker conditions, but the change in pupil dilation was similar for both groups. There was no effect of blink criteria on speech intelligibility or pupil dilation results for either group. However, the total percentage of blinks in the masker condition was significantly greater than in the quiet condition for the SSD group, which is consistent with previous studies that have found a relationship between blinking and task difficulty. This association should be carefully considered in future experiments using pupillometry to gauge listening effort.

II. Introduction

Effective, everyday communication is a complex skill requiring a myriad of peripheral and central auditory processes. Therefore, a single performance measure, such as a speech intelligibility score, fails to capture all aspects of listening. For example, speech intelligibility does not capture the amount of *effort* a listener expends. Listening effort is defined as the deliberate allocation of attention-related cognitive resources to perform difficult listening tasks (Pichora-Fuller et al., 2016). A participant's engagement or motivation to perform the task is also thought to contribute to the amount of effort they expend (Winn, Wendt, Koelewijn, & Kuchinsky, 2018). As such, individuals with the same intelligibility score may exert different amounts of effort due to individual factors, such as hearing or cognitive abilities (Ohlenforst et al., 2017; Zekveld, Kramer, & Festen, 2011). In fact, individuals with hearing loss generally report being more fatigued after an hour of listening and that noisy listening situations are more cognitively taxing compared to persons with normal hearing (NH) (Edwards, 2007; Zekveld, Kramer, & Festen, 2010). The documented differences in listening effort between hearing impaired and NH individuals are of interest because elevated effort is associated with stress and fatigue, and can also affect social interactions, thus negatively impacting quality of life (Alhanbali, Dawes, Millman, & Munro, 2019; Hughes, Hutchings, Rapport, McMahon, & Boisvert, 2018; Stephens & Hétu, 1991).

Numerous methods have been used to quantify listening effort, including subjective, behavioral, and physiological measures (McGarrigle et al., 2014). The measurement of pupil dilation, or pupillometry, is a particularly appropriate technique for tracking changes in the *time course* of effort. Task-evoked changes in pupil dilation are tightly coupled to the activity of noradrenergic neurons in the locus coeruleus (Aston-Jones & Cohen, 2005) and are therefore thought to be a time-sensitive index of attention and cognitive effort. The ability to capture changes in cognitive effort in real time is important because processing load is dynamic and may fluctuate throughout the duration of a stimulus (Winn et al., 2018). Furthermore, unlike other physiological measures that are subject to electrical and magnetic artifacts (e.g., functional magnetic resonance imaging, electroencephalography), pupillometry is compatible with amplification devices (e.g., hearing aids) and implantable devices (e.g., cochlear implants) (Friesen & Picton, 2010; Gilley et al., 2006; Wagner, Nagels, Toffanin, Opie, & Başkent, 2019). Additionally, pupillometry is relatively fast and inexpensive, making it a practical research technique and giving it the potential to be a valuable clinical tool (Winn et al., 2018).

While the utility of measuring pupil dilation to assess listening effort has been documented (Zekveld, Koelewijn, & Kramer, 2018), uniform methods for collecting, analyzing, and interpreting pupillometry data are still being established (Winn et al., 2018). Pupil dilation is a slow physiological response that can be contaminated by biological artifacts, such as blinking, gaze drifting, and participant movement, ultimately introducing noise into the data. Therefore, there is a need for data to be processed or cleaned before they are further analyzed. This process has not been well established across research groups, but reports suggest that data cleansing can include low-pass filtering, analysis and normalization of the baseline pupil measure, identification and rejection of corrupted trials, and de-blinking (Winn et al., 2018). In the present study, we focus on “de-blinking,” which refers to the interpolation of data points within a pupil track where the participant has blinked or where the pupil has been momentarily lost by the eyetracker. Of the three types of eye blinks that have been identified (spontaneous, reflexive, and voluntary), spontaneous blinks are likely the most prominent during pupillometry tasks because these are necessary for visual clarity and keeping the eye hydrated and occur in an extremely symmetrical and coordinated manner (Cruz, Garcia, Pinto, & Cechetti, 2011). Spontaneous blinks have been associated with numerous cognitive factors, including attention, information processing, speech production, and task difficulty (Stern, Walrath, & Goldstein, 1984; Tanaka & Yamaoka, 1993). However, the relationship between task difficulty and spontaneous blinks is unclear, with some studies reporting increased blink rate during more difficult tasks (e.g., Recarte, Pérez, Conchillo, & Nunes, 2019; Wood & Hassett, 1983) and others reporting blink inhibition (e.g., Holland & Tarlow, 1972, 1975; Zheng et al., 2012). These contradictory findings can be at least partially explained by the nature of the task, with reports of blink inhibition occurring more frequently in tasks involving a visual component compared with those that do not (Recarte et al., 2019; Stern et al., 1984). Recarte et al. (2019) investigated blink rate, pupil dilation, and subjective rating as a function of mental workload in young adults during three cognitive tasks: listening to speech, producing speech, and performing a mental arithmetic task. They found that each task elicited an increase in blink rate compared with the control condition. When participants were instructed to complete these tasks along with a visual search task, they still observed an increase in blink rate compared with the control condition, but the magnitude of increase was smaller than when there was no visual search task, thus demonstrating the complex relationship between blink rate and task modality. Of particular interest to the current study is their finding that the speech production and mental arithmetic tasks, which elicited the highest blink rates, also resulted in the largest pupil dilations and the highest subjective ratings of difficulty (Recarte et al., 2019). This suggests that blink rate and task difficulty are positively correlated for nonvisual tasks.

Some work has suggested that trials with more than 30% missing data should be discarded from analysis, as these trials may no longer contain meaningful information (Winn et al., 2018). However, other studies have used a more conservative criterion of 15% (e.g., Koelewijn, Zekveld, Festen, & Kramer, 2012; Zekveld & Kramer, 2014; Zekveld et al., 2011). To our knowledge, no work has clarified how a criterion is established, nor has there been a systematic investigation of its potential consequences. Due to the documented relationship between blink rate and cognitive load, it is important to ensure (a) that valid data are not being unnecessarily discarded and (b) that a chosen blink criterion does not skew results by disproportionately flagging difficult trials due to a higher proportion of spontaneous blinks.

Further, while several studies have investigated listening effort in individuals with bilateral hearing loss, there has been little focus on individuals with single-sided deafness (SSD), who have one ear with near-normal hearing and one with severe-to-profound sensorineural hearing loss. This is a timely population to study, as a number of these individuals are now pursuing cochlear implantation in an attempt to improve spatial hearing abilities and reduce debilitating effects of tinnitus. Outcomes thus far have been promising, with several studies reporting partial or full tinnitus suppression (Arndt et al., 2011; Buechner et al., 2010; Litovsky et al., 2019; Mertens, De Bodt, & Van de Heyning, 2016; Távora-Vieira, Marino, Krishnaswamy, Kuthbutheen, & Rajan, 2013), improved speech perception in noise (Bernstein, Goupell, Schuchman, Rivera, & Brungart, 2016; Gartrell et al., 2014), better sound localization abilities (Arndt et al., 2011; Gartrell et al., 2014; Litovsky et al., 2019; Vermeire & Van De Heyning, 2009; Zeitler et al., 2015), and improved quality of life after cochlear implantation (Arndt et al., 2011; Dillon et al., 2018; Firszt, Holden, Reeder, Waltzman, & Arndt, 2012; Härkönen et al., 2015; Távora-Vieira, Rajan, Van De Heyning, & Mertens, 2019; Vermeire & Van De Heyning, 2009). However, there is a lack of knowledge regarding how much cognitive load individuals with SSD exert in complex listening environments. This topic has clinical relevance in the context of determining whether cochlear implantation can facilitate reduced listening effort in addition to the aforementioned benefits for individuals with SSD.

The present study examined speech intelligibility and listening effort in individuals with SSD and with NH. Experimental methods differed slightly between SSD and NH listeners and will be presented as two separate experiments. The first aim of this study examined the effect of blink exclusion criteria on speech intelligibility, pupil dilation, and the number of trials included for analysis in each condition. This investigation is imperative due to the observed relationship between blinking and task difficulty and will help establish empirically validated methods for the analysis of pupillometry data. The second aim compared performance and listening effort between SSD and NH listeners to better understand the implications of listening with one ear in complex auditory environments as well as the possibilities for improvement following cochlear implantation.

III. Experiment 1: Listening Effort and Speech Intelligibility in Participants with SSD

A. Methods

a. Participants

Nine individuals with SSD were recruited as part of an ongoing clinical trial that is investigating the effect of cochlear implantation on a variety of auditory and cognitive domains in this population. Participants traveled to Madison, Wisconsin for the study, and testing took place at the University of Wisconsin- Madison Waisman Center over the duration of two days. Age of participants ranged from 26 to 69 years, and all were native English speakers. The etiology of hearing loss was sudden sensorineural hearing loss for seven participants, temporal bone fracture for one, and Meniere’s disease for one. The right ear was the poorer ear for all participants except two. Demographics are reported in Table 1. This study was approved by the University of Wisconsin-Madison Health Sciences Institutional Review Board.

b. Experimental Setup

Testing was conducted in a standard sound booth. Participants sat in a comfortable chair in front of a table with a fixed head mount, where they rested their chin and forehead. To ensure comfort, the height of the table and/or chair was adjusted for each participant. A computer monitor was attached to the table via an adjustable arm and was positioned so that it was approximately 65 cm away from the headrest. Illumination of the test room was set to 93 lux for all participants. The computer monitor background was set to a neutral color (medium gray) to avoid excessive pupil constriction or discomfort (Winn et al., 2018). A loudspeaker (Tannoy, Coatbridge, Scotland) was positioned at 0° azimuth at a height of 130 cm. Pupil size was measured in pixels using the "Area" setting on an eyetracker (Eyelink 1000 Plus). Pupil area was sampled at a rate of 1000 Hz using a proprietary algorithm developed by Eyelink manufacturers. The eyetracker camera was fixed to the table via a desktop mount 8 cm in front of the computer monitor.

c. Stimuli

Target stimuli were drawn from the Harvard Institute of Electrical and Electronics Engineers sentence corpus ("IEEE Recommended Practice for Speech Quality Measurements," 1969) and were recorded by a male talker. Masker stimuli (two-talker babble) consisted of AzBio sentences (Spahr et al., 2012) recorded by two different male talkers. Prior to testing, all stimuli were equalized to 85 dB sound pressure level (SPL)-A and stored as .wav files. During testing, stimuli were scaled to 65 dB SPL-A and played to the loudspeaker through a USB high-speed audio interface (RME Fireface, Haimhausen, Germany). Target sentences ranged from 4,000 to 6,000 ms in duration. Masker sentences were concatenated into a long sequence, and the starting sample of the maskers was randomly selected for each trial. Maskers began 250 ms prior to the onset of the target sentence and ended 250 ms after the offset of the target. A computer with customized software written in MATLAB (The MathWorks, Natick, MA) was used to deliver stimuli and collect data.

d. Procedure

Participants were tested in two conditions: (a) quiet, where the target was presented from 0° azimuth and (b) with speech maskers, where the target and maskers were both presented from 0° azimuth at a signal-to-noise ratio (SNR) of 0 dB. Prior to beginning the experiment, participants completed a familiarization procedure in which they heard six sentences in quiet, followed by 5 to 10 sentences with maskers. Stimuli for practice trials were randomly selected and then excluded from the test corpus to avoid any sentence repetitions.

During testing participants were instructed to fixate their gaze on a small cross in the center of the computer screen and attend to target sentences presented in quiet or in the presence of maskers. At the beginning of each trial the cross turned white to indicate that the trial was about to begin, and then a 1,000-ms baseline measurement in quiet was completed prior to the onset of the stimuli for all conditions. After stimulus offset, there was a 2,000 ms silent period to allow participants to think and prepare to respond. Participants were asked to repeat the target sentence after the 2,000 ms silent period. To prompt the verbal report of what was perceived, the cross on the screen turned green and the participant heard two beeps (Figure 1). Each sentence contained five key words, and an experimenter scored how many words the participant correctly repeated. The experimenter waited 10 to 15 s between trials to allow the pupil to return to baseline before beginning the next trial. Participants were encouraged to guess for sentences that they did not entirely hear. Frequent breaks were given throughout testing to avoid fatigue.

For both the quiet and masker conditions, stimuli were blocked into runs consisting of 15 sentences. Each participant was tested on at least two runs per condition. If time allowed, a third run was tested for the quiet condition. Research has shown that pupil tracks in easier conditions (e.g., speech perception in quiet) often contain more distortions and have more variability than tracks recorded in more difficult conditions (e.g., with maskers at a low SNR), which reliably elicit large changes in pupil dilation (Winn et al., 2018). If a condition only requires minimal cognitive resources, the pupil response may be small or may not rise above random pupillary oscillations that typically occur. Therefore, a higher number of trials are required to tease apart task-evoked changes in pupil size from noise or other sources of variability (e.g., movement, gaze drifting, etc.). Testing a higher number of trials in the quiet condition was intended to maximize the possibility that small responses would be distinguishable from noise and that an adequate amount of data would be available for analysis after discarding contaminated tracks. The order of conditions was randomized for each participant, and for each run, target stimuli were randomly selected from the corpus without repetition.

e. Data Analysis

This study examined the effect of processing pupillometry data with three different blink criteria: no more than 15%, 30%, or 45% of pupil track samples missing from the trial. As previously mentioned, task-evoked pupil dilation is susceptible to biologic artifacts, such as blinking, gaze drifting, and poor baseline measures, even when controlling for factors such as lighting and external distractions. While blinking is the principal cause of lost samples in a track, gaze drifting and equipment error can also contribute to the amount of missing data. At present, it is not possible to disentangle these artifact sources. Therefore, the term “blink” will be used to refer to all missing samples, regardless of the cause. For a given blink criterion, all tracks with greater than the specified amount of missing data were discarded from analysis. When calculating the percentage of missing samples in a track, only samples from the onset of the baseline to the end of the silent period were considered (Figure 1). The response period was not included in the analysis because this part of the pupil track is influenced by the motor response, and is therefore not purely related to task difficulty (Privitera, Renninger, Carney, Klein, & Aguilar, 2010; Winn, Edwards, & Litovsky, 2015). Consistent with methods for excluding contaminated trials from analysis, as described by Winn et al. (2018), tracks with vastly irregular baseline measurements, excessive distortions during the stimulus or silent period, or disproportionately large growth that is not typical of task-evoked changes in pupil dilation were also discarded. Further, tracks that contained a large section of missing data in a region of interest (e.g., during the wait period from which maximum pupil dilation is extracted) were also discarded, even if the percentage of missing data was below the specified blink criterion, as the interpolation could flatten the peak of the pupil response. In total, 1.6% of quiet trials and 0.7% of masker trials were discarded due to these types of contamination.

After discarding contaminated trials and processing the data using the three different blink criteria, the data for each condition were then “de-blinked” (i.e., linearly interpolated between gaps of missing data) and low pass filtered with a 10 ms time window using the “smooth” function in MATLAB. Methods for detecting blinks were in accordance with those described by Zekveld et al. (2010), where pupil dilations that fell below three standard deviations (SDs) from the mean were tagged as missing samples. The segments of missing data were linearly interpolated 80 ms before the blink and 160 ms following the blink in order to account for disturbances in pupil size caused by the eyelid opening and closing (Zekveld et al., 2010). Tracks were then baseline corrected by subtracting the baseline value (calculated by averaging the pupil response measured 1,000 ms before stimulus onset) (Figure 1), and then dividing by the baseline value in order to obtain the proportion of pupil change from baseline.[1] Finally, tracks were time-aligned to stimulus offset, and averaged together by condition for each participant.

Both maximum pupil dilation (i.e. maximum proportional change from baseline) and percentage of correctly repeated words were calculated for all included trials. The maximum pupil dilation was calculated during the 2,000 ms after the stimulus offset and before the response prompt, classified as the “silent period” (Figure 1). This period is considered to be a window where listeners process and plan for their response (Zekveld et al., 2010). While the latency for peak pupil dilation can vary across participants, this window has commonly been shown to elicit the greatest amount of pupil dilation throughout the trial for sentence-recognition tasks like the one used here (Winn et al., 2015, 2018).

f. Statistical Analysis

An alpha of 0.05 was used for all tests to determine whether results were significantly different from chance. Shapiro-Wilk normality tests were used to determine whether speech intelligibility and pupil dilation data were normally distributed. In order to reduce ceiling effects,

---

[1] In addition to divisive baseline correction, data were also analyzed using subtractive baseline correction (corrected pupil dilation = pupil dilation – baseline value). The baseline correction method did not change our results.

the speech intelligibility data were transformed into rationalized arcsine units (RAUs) prior to analysis (Studebaker, 1985). RAUs are analogous to percent correct scores in that higher values correspond to better performance. Separate approaches were used for normally distributed and non-normally distributed data to examine differences across conditions for each blink criterion. Either a matched-pairs t-test was used or a paired Wilcoxon signed-rank test was used, respectively.

In addition to investigating the effect of blink criteria on speech intelligibility and pupil dilation across conditions, we also examined potential bias towards discarding a higher number of difficult trials due to blinks. In other words, we examined the difference in the *number* of trials discarded per condition due to blinks exceeding the specified criterion. The goal of this analysis was to understand whether more trials were being discarded due to blinks in the masker condition compared to the quiet condition because of the proposed relationship between blinking and task difficulty. A Pearson's chi-square test of independence was used to determine whether the number of trials included for analysis under the least stringent (45%) and most stringent (15%) criteria was related to the difficulty of the condition (quiet versus masker). Finally, to further examine a potential relationship between condition difficulty and spontaneous blinks in our task, a matched-pairs t-test was used to assess whether the percentage of blinks in the masker condition was significantly different from the quiet condition under the most lenient blink criterion (45%).

B. Results

a. Effect of listening condition on speech intelligibility and pupil dilation

Figure 2 plots individual and average speech intelligibility in the quiet and masker conditions for each blink criterion. We expected participants to perform better in the quiet condition compared to the masker condition. In line with our prediction, all participants exhibited near-ceiling performance levels in the quiet condition, (e.g., scores under the 45% criterion ranged from approximately 98-100% correct). In contrast, with the same blink criterion, the masker condition yielded intelligibility scores between 24% and 64% correct across participants, demonstrating the large variability in performance that exists within this population (Figure 2, right panel). One-tailed matched-pairs t-tests confirmed that speech intelligibility in the quiet condition was significantly higher than in the masker condition for all blink criteria [15%: $t(8) = 10.75$, $p < 0.001$; 30%: $t(8) = 16.76$, $p < 0.001$; 45%: $t(8) = 16.96$, $p < 0.001$]. This finding indicates that, regardless of the blink criterion used to reject trials, speech intelligibility was more difficult in the 0 dB SNR masker condition than in the quiet condition.

Figure 3 shows individual and average maximum pupil dilation measured during the post-stimulus silent period for each participant in the quiet and masker conditions for the three blink criteria. We expected the masker condition to be more difficult and therefore elicit a larger maximum pupil dilation compared to the quiet condition. One-tailed Wilcoxon signed-rank tests found significant differences in pupil dilation across listening conditions for all blink criteria, with the masker condition resulting in larger maximum pupil dilation than the quiet condition [15%: $z = -2.67$, $p = 0.002$; 30%: $z = -2.67$, $p = 0.002$; 45%: $z = -2.67$, $p = 0.002$]. This result suggests that listeners exerted more effort, or task engagement, in the 0 dB SNR masker condition than in quiet.

b. Influence of blink criterion on number of trials analyzed

Table 2 contains the proportion of trials included for analysis under each blink criterion in the quiet and masker conditions. The least stringent blink criterion (45%) resulted in less than 10% of trials being discarded for both the quiet and masker conditions, while the most stringent (15%) resulted in approximately 22% of trials being discarded for the quiet condition and 27% for the masker condition. It should be noted that the data violated the assumption of independence, since the same participants were tested in the quiet and masker conditions. A Pearson's chi-squared test determined that there was no significant relationship between blink criterion and listening condition for the number of trials analyzed [$X^2(1) = 2.02$, $p = 0.169$]. This indicates that the number of included trials decreased similarly for both listening conditions as blink criterion stringency increased.

c. Relationship between percentage of blinks and condition

The current literature supports excluding pupil tracks which have greater than 15%-30% blinks or missing samples (Winn et al., 2018; Zekveld & Kramer, 2014; Zekveld et al., 2011). However, because maximum pupil dilation was very similar for the three blink criteria and the significant difference between listening conditions was present under all criteria, we opted to use only the 45% criterion for this analysis because it allowed for the highest proportion of trials to be included (see Table 2). Figure 4 illustrates the average percentage of blinks for each participant in the quiet versus masker condition. Previously observed relationships between task difficulty and blink rate led us to predict that the masker condition would elicit a higher blink rate, and consequently, a greater percentage of blinks than the quiet condition. We found that this was the case for all but two participants (MBD, MBG) (Figure 4). A two-tailed matched-pairs t-test revealed that the percentage of blinks was significantly higher in the masker condition compared to quiet condition [t(8) = -2.73, p = 0.026]. This indicates that there was a direct relationship between percentage of blinks and task difficulty for the SSD listeners tested in this study.

IV. Experiment 2: Listening Effort and Speech Intelligibility in Participants with Normal Hearing

A. Rationale

Experiment 1 examined whether a chosen blink criterion would systematically influence the results of a speech intelligibility and pupillometry task in individuals with SSD. In line with our expectations, intelligibility scores in the quiet condition were significantly better (Figure 2) and maximum pupil dilation was significantly smaller (Figure 3) than in the masker condition. This suggests that the masker condition was more difficult and demanded more effort, or engagement, than the quiet condition. Importantly, these results were unaffected by the level of blink criterion used to process the data. However, we did find that participants with SSD exhibited a significantly higher percentage of blinks in the speech masker compared to quiet condition. Due to the fact that Experiment 1 examined a small sample size drawn from a unique listening population, we sought to perform a parallel analysis on a larger, more generalizable population, namely NH listeners. The data set from NH listeners had originally been collected as part of a larger, separate study that was seeking to examine spatial unmasking and listening effort. Several of the conditions tested were identical to those analyzed in Experiment 1, and the data were collected using similar procedures and methods. One noteworthy difference between the methods in the two studies is that participants in the NH experiment were asked to refrain from blinking during the presentation of the stimulus in each trial. Therefore, we investigated the effect of blink criterion on the results of a younger group of NH listeners who were given explicit instructions not to blink. The data were also compared to the SSD data in order to enhance our understanding of the implications of unilateral listening in complex acoustic environments.

B. Methods

All methods and procedures were identical to those used in Experiment 1 unless otherwise specified.

a. Participants

Twenty participants were recruited from the community; all passed a hearing screening (20 dB HL at octave frequencies from 250-8000 Hz). Testing took place at the University of Wisconsin-Madison Waisman Center over the duration of two sessions that were scheduled at least one week apart. The age of participants ranged from 18-45 years (mean ± SD = 21.90 ± 6.17), and all were native English speakers. This study was approved by the University of Wisconsin-Madison Health Sciences IRB.

b. Stimuli

Target stimuli were drawn from the Harvard Institute of Electrical and Electronics Engineers sentence corpus ("IEEE Recommended Practice for Speech Quality Measurements," 1969). After the start of the SSD study, our lab re-recorded many of our speech materials in order to create a database with a large inventory of high-quality stimuli. Therefore, the target sentences for the NH study were recorded by a different male talker than stimuli used for

Experiment 1. Masker stimuli (two-talker babble) consisted of AzBio sentences (Spahr et al., 2012) spoken by the same male talkers as in Experiment 1. A computer with customized software written in MATLAB (The MathWorks, Natick, MA) was used to deliver stimuli and collect data.

c. *Procedure*

Participants were tested in three conditions: (1) quiet, where the target was presented from 0° azimuth at 65 dB SPL-A, (2) with speech maskers, where the target and maskers were both presented from 0° azimuth at an SNR of 0 dB, and (3) with speech maskers, where the target and maskers were both presented from 0° azimuth at an SNR of -12 dB. The first two conditions were identical to those tested in Experiment 1. The third condition with a harder SNR was included in order to analyze a wider range of performance in NH listeners. Prior to beginning the experiment on each day of testing, participants completed a familiarization procedure in which they heard a minimum of 12 sentences with maskers. Stimuli for practice trials were randomly selected and then excluded from the test corpus to avoid any sentence repetitions.

For both the quiet and masker conditions, stimuli were blocked into runs consisting of eight sentences. Each participant completed four runs per listening condition. The order of conditions was randomized for each participant, and for each run, target stimuli were randomly selected from the corpus without replacement. Maximum pupil dilation and percentage of correctly repeated words were analyzed for each condition.

d. *Data Analysis*

Akin to Experiment 1, the objective of this study was to examine the effect of processing pupillometry data with three different blink criteria: no more than 15%, 30%, or 45% of trial samples missing from the track. In total, 5.2% of quiet trials, 3.9% of 0 SNR masker trials, and 0.5% of -12 SNR masker trials were discarded due to the types of contamination explained in the Experiment 1 “Data analysis” section. Both maximum pupil dilation (proportion change from baseline) and percentage of correctly repeated words (transformed to RAUs) were calculated for all included trials by means of the same MATLAB analysis code used in Experiment 1.

e. Statistical Analysis

An alpha of 0.05 was used for all tests to determine whether results were significantly different from chance. For speech intelligibility, pupil dilation, and percentage of blinks data, Shapiro-Wilk normality tests determined that one or more of the conditions were not normally distributed. Consequently, Friedman’s analysis of variance (ANOVA) tests were used to examine these measures across conditions for each blink criterion. Post hoc pairwise comparisons were completed using one-tailed Wilcoxon signed-rank tests with Bonferroni corrections for multiple comparisons. To investigate a potential bias towards discarding a higher number of difficult trials due to blinking, a Pearson’s chi-squared test of independence was used to determine whether the number of trials included for analysis under the least stringent (45%) and most stringent (15%) criteria was related to the condition (quiet versus 0 SNR speech masker versus -12 SNR speech masker). Finally, two-tailed independent samples t-tests for normally distributed data or two-tailed Mann-Whitney U tests for non-normally distributed data were used to compare speech intelligibility, pupil dilation, and percentage of blinks across the SSD and NH groups.

C. Results

a. Effect of listening condition on speech intelligibility and pupil dilation

Figure 5 plots individual and average speech intelligibility in the quiet and masker conditions for each blink criterion. We expected performance to be best in the quiet condition and worst in the -12 SNR masker condition, with the 0 SNR masker condition falling in between. All participants exhibited near ceiling-level performance in the quiet condition (median score under the 45% criterion = 116.50%) (Figure 5, left panel). Performance was also high in the 0 dB SNR speech masker condition, with the median score under the 45% criterion equaling 95.32%. In contrast, the -12 dB SNR speech masker condition elicited much lower scores, with the median equaling 37.32% (Figure 5, right panel). Friedman's ANOVAs indicated that speech intelligibility differed significantly across listening conditions for all blink criteria [45%: $X^2(2) = 40.00$, $p < 0.001$; 30%: $X^2(2) = 40.00$, $p < 0.001$; 15%: $X^2(2) = 40.00$, $p < 0.001$]. Post hoc pairwise comparisons revealed that speech intelligibility in the quiet condition was significantly higher than the 0 SNR [45%: $z = -3.92$, $p < 0.001$; 30%: $z = -3.92$, $p < 0.001$; 15%: $z = -3.92$, $p < 0.001$] and -12 SNR masker conditions [45%: $z = -3.92$, $p < 0.001$; 30%: $z = -3.92$, $p < 0.001$; 15%: $z = -3.92$, $p < 0.001$], and that speech intelligibility in the 0 SNR masker condition was significantly higher than the -12 SNR masker condition [45%: $z = -3.92$, $p < 0.001$; 30%: $z = -3.92$, $p < 0.001$; 15%: $z = -3.92$, $p < 0.001$]. This indicates that speech intelligibility decreased as the masker level was increased. Blink criteria did not affect this result.

Figure 6 shows maximum pupil dilation measured during the post-stimulus silent period for each participant in the quiet and masker conditions as well as the average for the three blink criteria. We expected pupil dilation to be smallest in the quiet condition and highest in the -12

SNR masker condition, with the 0 SNR masker condition falling in between. Friedman's ANOVAs indicated that maximum pupil dilation differed significantly across conditions for all blink criteria [45%: $X^2(2) = 31.60$, $p < 0.001$; 30%: $X^2(2) = 31.60$, $p < 0.001$; 15%: $X^2(2) = 27.90$, $p < 0.001$]. Post hoc pairwise comparisons revealed that maximum pupil dilation in the quiet condition was significantly smaller than the 0 SNR [45%: $z = -3.02$, $p = 0.002$; 30%: $z = -2.99$, $p = 0.003$; 15%: $z = -3.17$, $p = 0.001$] and -12 SNR masker conditions [45%: $z = -3.92$, $p < 0.001$; 30%: $z = -3.92$, $p < 0.001$; 15%: $z = -3.92$, $p < 0.001$], and that pupil dilation in the 0 SNR masker condition was significantly smaller than the -12 SNR masker condition [45%: $z = -3.92$, $p < 0.001$; 30%: $z = -3.92$, $p < 0.001$; 15%: $z = -3.36$, $p < 0.001$]. This indicates that effort or engagement increased with increasing difficulty of the listening condition. This finding was present across all blink criteria.

b. *Influence of blink criterion on number of trials analyzed*

Table 3 contains the proportion of trials included for analysis under each blink criterion in the quiet and speech masker conditions. The least stringent blink criterion (45%) resulted in less than 1% of trials being discarded for the quiet and both masker conditions, while the most stringent blink criterion (15%) resulted in approximately 11% of trials being discarded for all three conditions. A Pearson's chi-squared test determined that there was no significant relationship between blink criterion and listening condition for the number of trials analyzed [$X^2(2) = 0.34$, $p = 0.849$]. Consistent with the SSD group results, this indicates that the change in number of trials analyzed across blink criteria was similar between the quiet and masker conditions for the NH listeners.

c. Relationship between percentage of blinks and listening condition

A Friedman’s ANOVA determined that the total percentage of blinks under the 45% blink criterion did not significantly differ by listening condition [$X^2(2) = 0.70$, p = 0.773], unlike results in Experiment 1.

d. Comparison of SSD and NH data: Quiet and 0 SNR speech masker conditions

Since blink criteria did not influence the results of either experiment, between-group comparisons were conducted using the most lenient blink criterion (45%). Because SSD participants were not tested in the -12 SNR condition, between-group comparisons included only the quiet and 0 SNR masker conditions. While speech intelligibility was similar across groups in the quiet condition (SSD mean = 112.37% ± 2.12, NH mean = 115.31% ± 4.90), performance diverged in the speech masker condition, with the SSD group averaging 49.20% ± 11.42 and the NH group averaging 95.92% ± 5.85. In order to evaluate the effect of noise on speech intelligibility and listening effort in NH and SSD listeners, the differences between the quiet and 0 SNR speech masker condition were compared across groups for both measures (Figure 7). We predicted the SSD group to be more negatively impacted by the noise maskers than the NH group due to their inability to access binaural benefits, and consequently to also show a larger increase in pupil dilation across conditions compared to the NH group. On average, the NH group’s intelligibility decreased by 19.39% when speech maskers were added, while the SSD group’s intelligibility decreased by an average of 63.17% (Figure 7A). A two-tailed independent samples t-test confirmed that the SSD group’s intelligibility decreased significantly more than the NH group’s from the quiet to speech masker condition [t(27) = -13.16, p < 0.001]. This indicates that the SSD group’s speech intelligibility performance was much more negatively impacted by the addition of speech maskers compared to the NH group. The changes in maximum pupil dilation (Figure 7B) from the quiet to speech masker condition, on the other hand, were not significantly different between the SSD and NH group [Mann-Whitney U test: $z(n_1 = 9, n_2 = 20) = 1.74$, $p = 0.085$]. However, it should be noted that, in the masker vs. quiet conditions, the SSD group exhibited a larger increase in pupil dilation than the NH group (SSD median difference = 0.17; NH median difference = 0.08).

Finally, percentage of blinks in the quiet and 0 SNR masker conditions were compared across groups. We expected to see differences across groups due to the discrepancy in blink instruction for each experiment (SSD participants were given no instruction regarding blinking, NH participants were instructed to avoid blinking during each trial). The SSD group median percentages were 7.16% in the quiet condition and 8.52% in the masker condition, while the NH group medians were 4.65% blinks in the quiet condition and 4.72% in the masker condition, demonstrating that the percentage of blinks for NH group was less than for the SSD group. Percentage of blinks was compared across groups for each condition separately. Two-tailed Mann-Whitney U tests found the difference in percentage of blinks across groups to be non-significant for either condition [Quiet: $z(n_1 = 9, n_2 = 20) = -1.27$, $p = 0.216$; 0 SNR speech masker: $z(n_1 = 9, n_2 = 20) = -1.89$, $p = 0.062$].

V. Discussion

Pupillometry has become an increasingly popular method for capturing changes in mental effort over time, and is especially well suited for populations with assistive devices made of ferrous material that are incompatible with other objective methods like functional magnetic resonance imaging and electroencephalography (Friesen & Picton, 2010; Gilley et al., 2006;

Wagner et al., 2019). However, many methods for cleaning and analyzing pupillary data have yet to be empirically investigated. The first aim of this study was to investigate the effect of a common exclusion criterion, percentage of blinks, on speech intelligibility and maximum pupil dilation in individuals with SSD and with NH. Participants were tested in quiet and with speech maskers. We chose to examine this particular trial exclusion criterion because blinking has been related to task difficulty and is a major determinant for excluding pupil tracks from analysis in the pupillometry literature. The second aim was to compare performance and listening effort between the SSD group and NH group. Due to the severity of hearing loss in one ear, individuals with SSD have restricted access to spatial cues, often reporting fatigue and effortful listening (Alhanbali, Dawes, Lloyd, & Munro, 2017; Dillon et al., 2018; Grantham et al., 2012; Litovsky et al., 2019; Távora-Vieira et al., 2019). Examining listening effort in this population enhances our understanding of the compensatory mechanisms that individuals with hearing loss employ to successfully function in everyday, complex listening situations.

For both the SSD and NH group, we found significant differences in speech intelligibility and maximum pupil dilation in the quiet condition compared to the conditions with a speech masker. In line with our expectations, intelligibility scores in the quiet condition were significantly better (Figures 2 and 5) and maximum pupil dilation was significantly smaller (Figures 3 and 6) compared to the 0 SNR masker condition. This suggests that masker conditions were more difficult and demanded more effort or engagement than the quiet condition for both groups. For the NH group, this trend was maintained for the -12 SNR masker condition, in which listeners demonstrated significantly poorer speech intelligibility scores and greater pupil dilation compared to the 0 SNR masker condition. These findings did not change based on the level of blink criterion used to process the data.

We examined the total percentage of blinks in both the quiet and speech masker conditions to investigate a potential relationship between spontaneous blinking and task difficulty in our study. We found that the masker condition elicited a significantly higher percentage of blinks compared to the quiet condition for the SSD listeners (Figure 4). This observation is consistent with previous studies that have demonstrated a significant positive relationship between blink rate and task difficulty (e.g., Recarte et al., 2008). The present study also examined the proportion of trials analyzed under three blink criteria, and found that the quiet and masker conditions were similar under the 45% criterion (93% and 94% included for analysis, respectively), and began to diverge under the more stringent 15% criterion (78% and 73% included for analysis, respectively) (Table 2). This trend did not reach significance, but when considered in tandem with the significant relationship between blink percentage and condition, it may suggest that a stringent criterion like 15% could result in a higher proportion of trials being discarded from analysis in difficult conditions. This effect also has the potential to manifest within a condition, with a stringent blink criterion resulting in the exclusion of trials that were more difficult (and had higher pupil dilation), thereby underestimating pupil dilation for the condition and consequently, listening effort or engagement. This did not appear to be the case for our study since pupil dilation for a given condition appeared to be similar across all blink criteria (Figure 3). In contrast, we did not observe similar trends regarding percentage of blinks in each condition or proportion of trials analyzed under each criterion for the NH data. A Freidman's ANOVA revealed that the total percentage of blinks did not differ between conditions, nor was there a difference in proportion of trials kept between conditions under any of the blink criteria. However, these results must be interpreted with caution because of the explicit instructions given to NH listeners to refrain from blinking during each trial.

To examine differences between the SSD and NH groups, we compared changes in performance from the quiet to 0 SNR masker condition across groups. Due to the well-established benefits that result from access to binaural hearing in noisy environments (e.g., Hawley, Litovsky, & Culling, 2004; Litovsky, Parkinson, & Arcaroli, 2009; Moore, 2003) we expected SSD listeners to be more negatively impacted by the addition of a speech masker than the NH listeners. Our findings confirmed this expectation, with both groups scoring similarly in the quiet condition, but the NH listeners scoring an average of 47% better than the SSD listeners in the speech masker condition (Figure 7). This effect has been shown in previous studies as well. Rothpletz et al. (2012) compared speech reception thresholds of individuals with NH to those with unilateral hearing loss in both a monaural headphone condition and in a co-located free field condition using the Coordinate Response Measure (CRM) corpus as both the target and masker stimuli. Their results revealed no difference in performance between the groups on the monaural headphone task. However, when tested in the co-located free field condition, individuals with unilateral hearing loss performed significantly worse than those with NH, with a difference of about 4.5 dB between thresholds for each group. The results shown by the Rothpletz et al. (2012) study as well as the current study were obtained in co-located target and masker conditions, which lack interaural differences that could be used to separate the two auditory streams. However, in this situation listeners with two ears do have access to a binaural advantage known as binaural redundancy, or the benefit that listeners receive by having duplicate copies of a signal in the two ears. Binaural redundancy has been shown to result in improved speech intelligibility in noise and increased perceptual loudness (Hawley et al., 2004; Litovsky et al., 2009). Individuals with SSD may be at a disadvantage because they are unable to access these benefits.

In addition to speech intelligibility, we also examined changes in pupil dilation from the quiet to the speech masker condition across groups. Compared with NH listeners, SSD listeners demonstrated a greater decrease in performance from the quiet condition to the speech masker condition. Thus, we expected SSD listeners to exhibit a greater change in pupil dilation between conditions than the NH listeners. While our results were consistent with the expected trend, the difference between groups was not significant ($p = 0.085$). One possible explanation is the large age discrepancy between listeners in the SSD and NH groups (SSD mean ± SD = 52.22 ± 14.12; NH mean ± SD = 21.90 ± 6.17). Previous studies have found interactions between aging, hearing loss and pupillary responses. Kramer et al. (2016) reported that the difference in pupil dilation between quiet and $\text{SRT}_{50\%}$ conditions was smaller for hearing-impaired listeners than NH listeners. Hearing-impaired listeners had similar pupil dilation to NH listeners in the quiet condition, but significantly smaller pupil dilation in the $\text{SRT}_{50\%}$ condition, despite the fact that they rated the $\text{SRT}_{50\%}$ condition as more effortful than the NH listeners. Comparable results were also reported by Zekveld et al. (2011). Effects similar to these may have contributed to the lack of significant difference in pupil dilation change between the two groups in our study. Zekveld et al. (2011) found that middle-aged listeners demonstrated relatively small peak pupil dilations at difficult SNRs and relatively long pupil responses, compared to younger listeners. They proposed that middle-aged listeners do not encode and process speech as deeply as younger individuals (i.e., there is less memory and semantic encoding), and that “aging is associated with increased speech processing time” (Zekveld et al., 2011). These concepts are supported by numerous studies that have demonstrated age-related decline in cognitive functions including working-memory (e.g., Gordon-Salant & Fitzgibbons, 1997; for review, see Salthouse, 2010), and compensatory mechanisms to overcome these deficits, including an upregulation of “nontraditional language-related” brain regions and prolonged activation during language processing (Wingfield & Grossman, 2006). Additionally, Piquado, Isaacowitz, and Wingfield (2010) proposed a potential age-related change in pupil reactivity, where the pupil becomes less responsive as individuals get older. Based on these explanations, had we tested a NH group that was more similar in age to the SSD group, it is possible we may have seen a larger effect of group on the change in pupil dilation from quiet to speech masker conditions. Another explanation may be the large variability of the NH group, which is likely due to the aforementioned effects of aging and hearing loss on the pupil response. The group contained one strong outlier with a value that was greater than 2.5 times the interquartile range. In order to ensure that the outlier was not affecting the results of the statistical test, the outlier was removed and replaced by a value that was the mean plus two SDs (mean = 0.08, SD = 0.09) (Field, 2013), however, this transformation did not change the test statistic.

A. *Implications for pupillometry data analysis*

Blink criterion stringency did not affect speech intelligibility or pupil dilation results for the SSD or NH group. However, we found a significant difference in the total percentage of blinks in the quiet versus speech masker conditions for the SSD group, but not for the NH group. In the present study, we were not able to deduce whether this was due to the lack of blink instruction given to the SSD group, participant demographics (e.g., age and hearing ability) of the SSD group, or a combination of the two. Additionally, our findings are limited by our small sample size. The discrepancy in results and difference in instructions across groups makes it difficult to conclude what should be done regarding blink exclusion criteria. Based on the findings of the SSD group analysis, a conservative recommendation may be to use a more lenient blink criterion (e.g., 30-45%) in order to promote data retention and avoid inadvertently skewing results, which may conceal important information about task difficulty. However, this recommendation may not hold for studies utilizing a different trial structure or shorter stimuli than those presented in this study. Additionally, it is imperative that an experimenter visually inspect individual pupil tracks, especially when utilizing a more lenient blink criterion. Tracks that contain a large section of missing data in an important section of the pupil track (e.g., during the wait period from which maximum pupil dilation is extracted) should be discarded, as the interpolation may flatten the peak of the pupil response. Furthermore, while we cannot say for certain whether the higher percentage of blinks for SSD listeners compared to NH listeners was entirely due to the difference in blink instruction, experimenters should give careful thought to the instructions they give, as asking participants to refrain from blinking can improve data quality but may also impose an additional attention-demanding task on participants (Berman, Horovitz, Morel, & Hallett, 2012). Further research is needed in order to better understand these relationships, but the present study demonstrates that blink criterion stringency deserves careful consideration in future experiments using pupillometry to gauge listening effort.

VI. Limitations

It is promising that the results of our experiment were not affected by the level of blink criteria used to analyze the data, however, these conclusions are limited by our small sample sizes and differing instructions between Experiment 1 and Experiment 2. Other analytical techniques that make use of curve fitting (e.g., growth curve analysis, generalized additive [mixed] models) could be even more robust to different criterion levels, as they do not depend on the integrity of a single data point. Further, in the present study, only a small portion of the entire pupil track was analyzed to determine maximum pupil dilation (i.e., silent period). Due to the changing task demands throughout the course of the trial (e.g., listening, processing, and responding), participants' blink rate likely varies systematically within a trial. It is conceivable that other portions of the trial may have been more affected by spontaneous blinks related to task difficulty. Therefore, these results are only generalizable to experiments with trial structures and analysis windows similar to those used in this study. Finally, it is also possible that results from such a unique population may not be generalizable to individuals with other types and/or degrees of hearing loss, or to individuals with devices like hearing aids or cochlear implants, since all of these factors contribute to patient performance and processing demands.

VII. Summary

In conclusion, the present study revealed that speech intelligibility was better and maximum pupil dilation was smaller in quiet listening conditions compared to noisy conditions in individuals with SSD and with NH. A systematic analysis of blink exclusion criteria showed that varying criterion stringency did not alter the effects observed across quiet and speech masker conditions for speech intelligibility or maximum pupil dilation for either group. Nevertheless, we did find a significantly higher percentage of blinks in the masker condition relative to the quiet condition in the SSD group, suggesting that blink criterion stringency should be carefully considered in studies using pupillometry to measure listening effort.

Acknowledgements

This research was supported by NIH-NIDCD Grant No. R01DC003083 (to RYL), NIH-NICHD Grant No. U54HD090256 (to Waisman Center), and by funds provided by the University of

Wisconsin-Madison Department of Surgery to J. Roche. Portions of this work were presented at the 2019 Conference on Implantable Auditory Prostheses, Lake Tahoe, CA, July 2019. The authors would like to thank Shelly P. Godar and Ellen Snodgrass for help with recruitment and data collection, and members of the Binaural Hearing and Speech Lab for assistance with data collection.

Disclaimer

The identification of specific products or scientific instrumentation is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the author, DoD, or any component agency. The views expressed in this article are those of the author and do not reflect the official policy of the Department of Army/Navy/Air Force, Department of Defense, or U.S. Government.

VIII. Figures and Tables

Table 1

Participant ID	Age (yrs;mo)	Duration of Deafness (years)	Better Ear Pure Tone Average (dB HL)	Poorer Ear Pure Tone Average (dB HL)
MBA	47	3	16.67	No testable hearing
MBB	46	5	5.00	63.33
MBC	67	1	11.67	No testable hearing
MBD	48	2	10.00	93.33
MBE	26	1	8.33	108.33
MBF	44	1	21.67	100.00
MBG	55	1	13.33	70.00
MBI	69	8	13.33	No testable hearing
MBJ	68	2	13.33	83.33

Table 1. Participant demographic information. Pure tone average was defined as the average hearing threshold in dB HL of 500 Hz, 1000 Hz, and 2000 Hz.

Table 2

	Blink Criterion		
Condition	15% Blink Criterion	30% Blink Criterion	45% Blink Criterion
Quiet	0.78	0.90	0.94
0 dB SNR Speech Masker	0.73	0.89	0.93

Table 2. Proportion of trials analyzed under each blink criterion in quiet and speech masker conditions for the SSD group.

Table 3

	Blink Criterion		
Condition	15% Blink Criterion	30% Blink Criterion	45% Blink Criterion
Quiet	0.89	0.99	0.99
0 dB SNR Speech Masker	0.88	0.99	0.99
-12 dB SNR Speech Masker	0.89	0.99	1.00

Table 3. Proportion of trials analyzed under each blink criterion in quiet and speech masker conditions for the NH group.

Figure 1

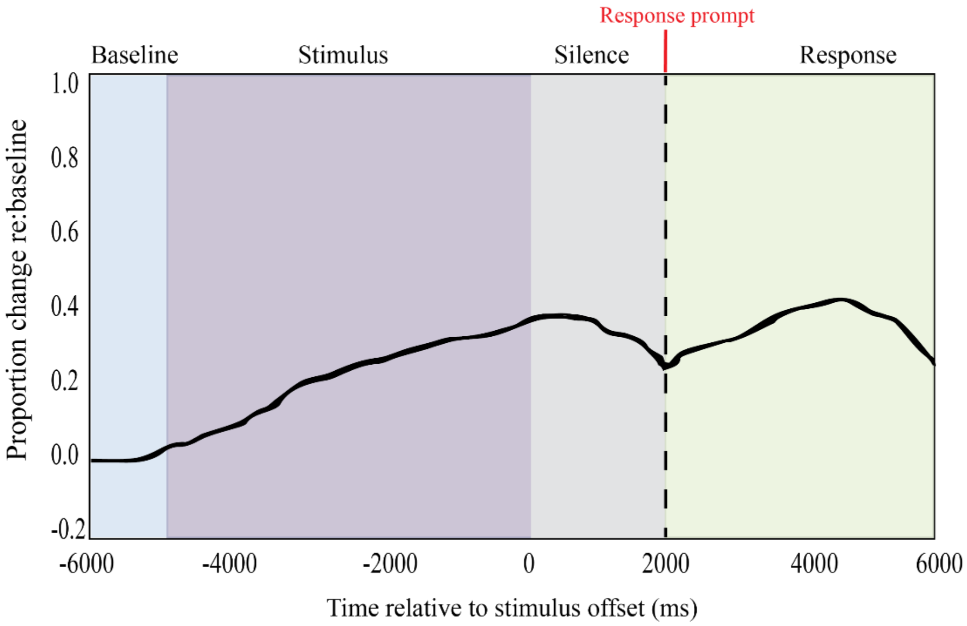


Figure 1. Example of a pupil track. Baseline pupil dilation was measured 1,000 ms prior to stimulus onset, the stimulus was then presented, there was a 2,000 ms silent period, participants heard two beeps to prompt a verbal response (dashed line), and then listeners repeated what they perceived.

Figure 2

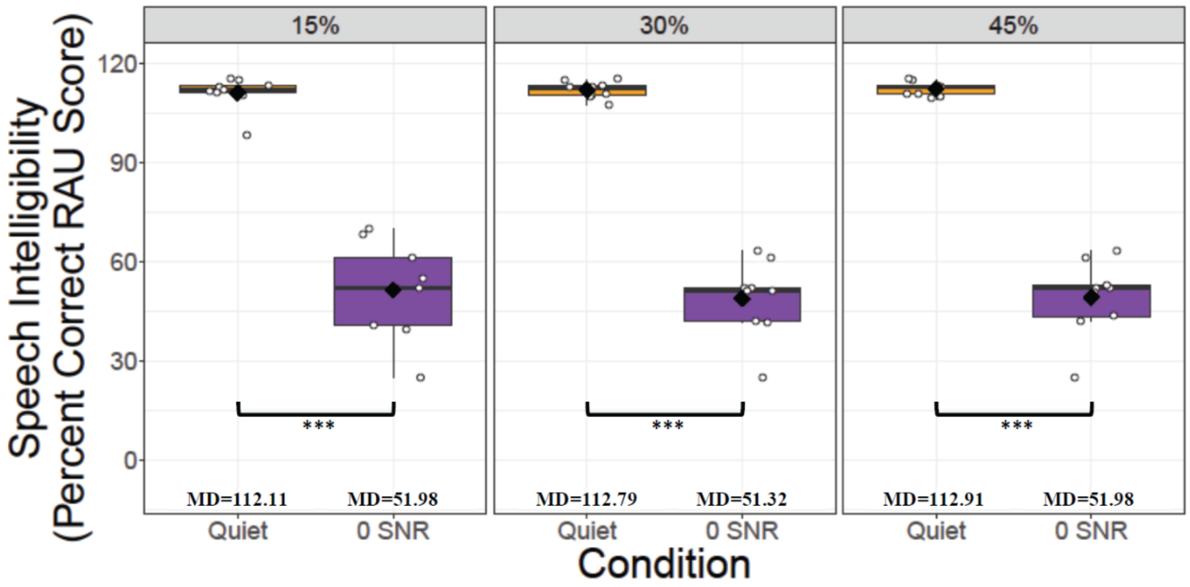


Figure 2. Speech intelligibility scores for the SSD group measured as percent of correctly repeated words in the quiet condition and the 0 dB SNR speech masker condition using 15%, 30%, and 45% blink criteria. Data were transformed to rationalized arcsine units (RAUs) for analysis. Black diamonds indicate means for each blink criterion, and small white circles represent individual participants. Group medians (MD) are represented in the box plot by the solid black line and denoted below each plot. Points have been horizontally jittered for visibility. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 3

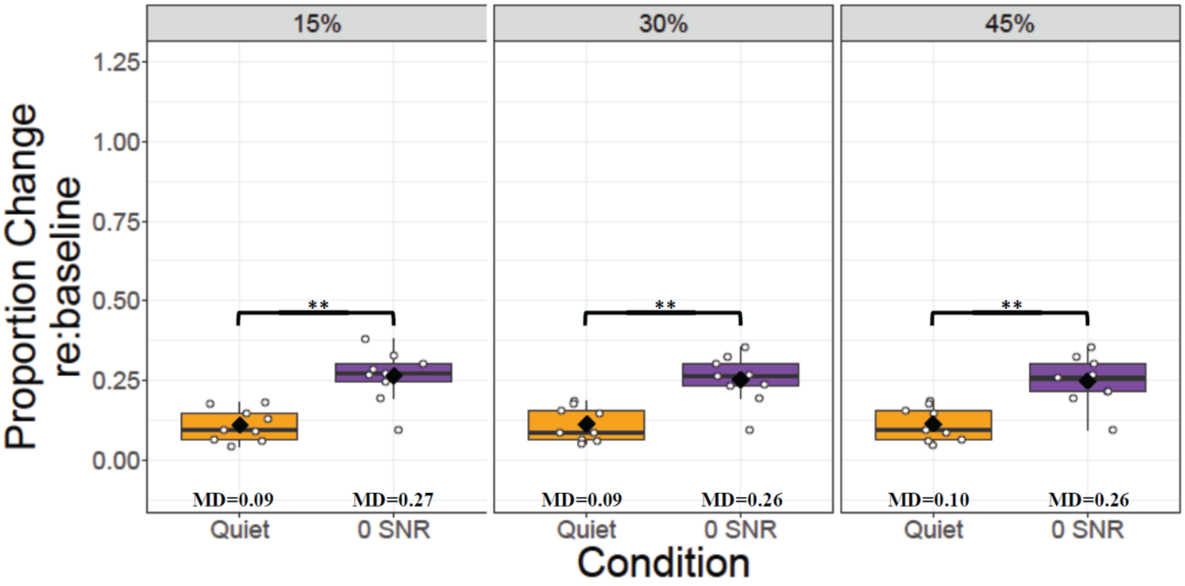


Figure 3. Maximum pupil dilation for the SSD group plotted as proportion change from baseline using 15%, 30%, and 45% blink criteria. Maximum dilation is calculated in the post-stimulus silent period of the task (2,000 ms window between stimulus offset and response prompt). Black diamonds indicate means for each blink criterion and small white circles represent individual participants. Group medians (MD) are represented in the box plot by the solid black line and denoted below each plot. Points have been horizontally jittered for visibility. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 4

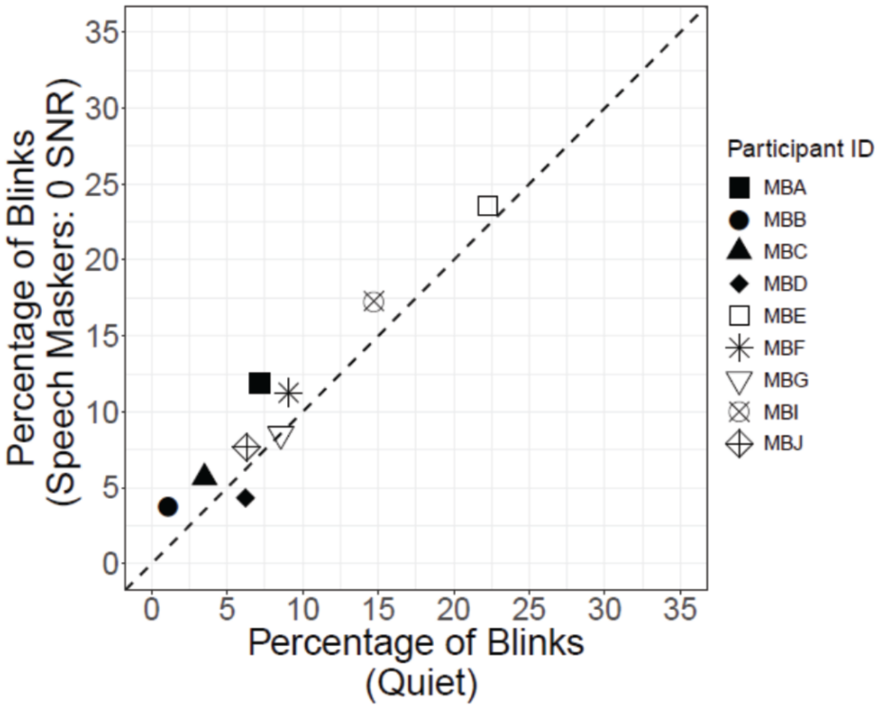


Figure 4. Comparison plot showing the percentage of blinks for each SSD participant for the 0 dB SNR speech masker condition as a function of the quiet condition. The dashed line denotes a line of equivalence. Values below this line indicate that the percentage of blinks in the quiet condition was greater than in the speech masker condition. Points above this line indicate that the percentage of blinks in the speech masker condition was greater than in the quiet condition.

Figure 5

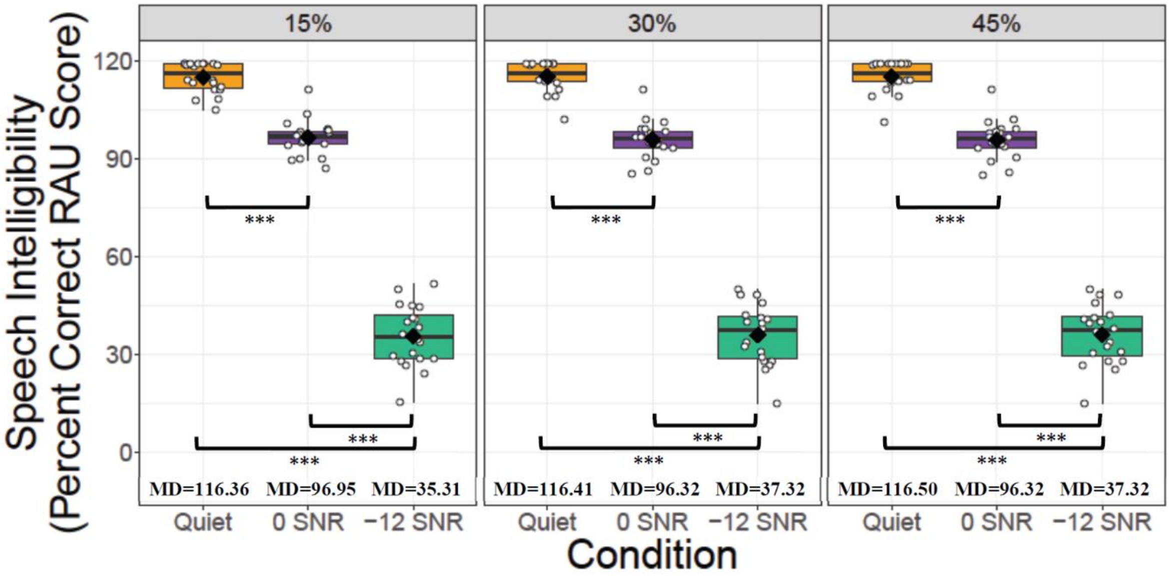


Figure 5. Speech intelligibility scores for the NH group measured as percent of correctly repeated words in the quiet condition and the speech masker conditions using 15%, 30%, and 45% blink criteria. Data were transformed to rationalized arcsine units (RAUs) for analysis. Black diamonds indicate means for each blink criterion and small white circles represent individual participants. Group medians (MD) are represented in the box plot by the solid black line and denoted below each plot. Points have been horizontally jittered for visibility. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 6

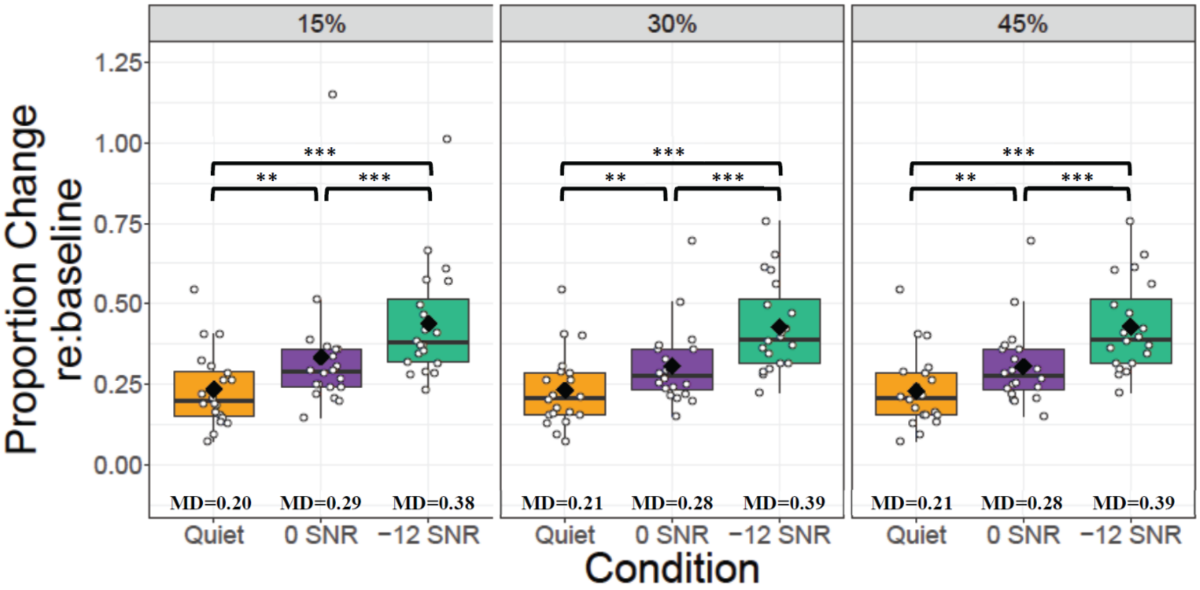


Figure 6. Maximum pupil dilation for the NH group plotted as proportion change from baseline using 15%, 30%, and 45% blink criteria. Maximum dilation is calculated in the post-stimulus silent period of the task (2,000 ms window between stimulus offset and response prompt). Black diamonds indicate means for each blink criterion and small white circles represent individual participants. Group medians (MD) are represented in the box plot by the solid black line and denoted below each plot. Points have been horizontally jittered for visibility. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 7.

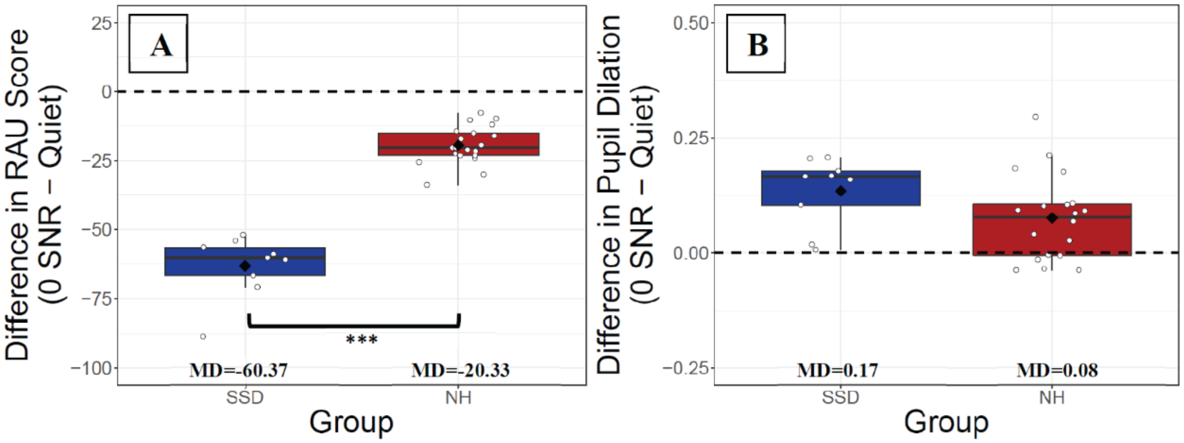


Figure **7A**: Comparison of SSD and NH groups. The difference in speech intelligibility scores (transformed to RAUs) between conditions for the SSD and NH groups under the 45% blink criterion. **7B**: The difference in maximum pupil dilation between conditions for the SSD and NH groups under the 45% blink criterion. The differences were calculated as the 0 SNR masker condition minus the quiet condition. Black diamonds indicate means for each group and small white circles represent individual participants. Group medians (MDs) are represented in the box plots by the solid black line and denoted below each plot. Points have been horizontally jittered for visibility. Asterisks indicate the significance level of the across-group comparison (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

IX. References

Alhanbali, S., Dawes, P., Lloyd, S., & Munro, K. J. (2017). Self-Reported Listening-Related Effort and Fatigue in Hearing-Impaired Adults. *Ear and Hearing*, *38*(1), e39–e48. https://doi.org/10.1097/AUD.0000000000000361

Alhanbali, S., Dawes, P., Millman, R. E., & Munro, K. J. (2019). Measures of Listening Effort Are Multidimensional. *Ear and Hearing*, *40*(5), 1084–1097. https://doi.org/10.1097/AUD.0000000000000697

Arndt, S., Aschendorff, A., Laszig, R., Beck, R., Schild, C., Kroeger, S., … Wesarg, T. (2011). Comparison of pseudobinaural hearing to real binaural hearing rehabilitation after cochlear implantation in patients with unilateral deafness and tinnitus. *Otology and Neurotology*, *32*(1), 39–47. https://doi.org/10.1097/MAO.0b013e3181fcf271

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Berman, B. D., Horovitz, S. G., Morel, B., & Hallett, M. (2012). Neural correlates of blink suppression and the buildup of a natural bodily urge. *NeuroImage*, *59*(2), 1441–1450. https://doi.org/10.1016/j.neuroimage.2011.08.050

Bernstein, J. G. W., Goupell, M. J., Schuchman, G. I., Rivera, A. L., & Brungart, D. S. (2016). Having two ears facilitates the perceptual separation of concurrent talkers for bilateral and single-sided deaf cochlear implantees. *Ear and Hearing*, *37*(3), 289–302. https://doi.org/10.1097/AUD.0000000000000284

Buechner, A., Brendel, M., Lesinski-Schiedat, A., Wenzel, G., Frohne-Buechner, C., Jaeger, B., & Lenarz, T. (2010). Cochlear implantation in unilateral deaf subjects associated with ipsilateral tinnitus. *Otology and Neurotology*, *31*(9), 1381–1385. https://doi.org/10.1097/MAO.0b013e3181e3d353

Cruz, A. A. V., Garcia, D. M., Pinto, C. T., & Cechetti, S. P. (2011). Spontaneous eyeblink activity. *Ocular Surface*, Vol. 9, pp. 29–41. https://doi.org/10.1016/S1542-0124(11)70007-6

Dillon, M. T., Buss, E., Rooth, M. A., King, E. R., Deres, E. J., Buchman, C. A., … Brown, K. D. (2018). Effect of Cochlear Implantation on Quality of Life in Adults with Unilateral Hearing Loss. *Audiology and Neurotology*, *22*(4–5), 259–271. https://doi.org/10.1159/000484079

Edwards, B. (2007). The Future of Hearing Aid Technology. *Trends in Amplification*, *11*(1), 31–45. https://doi.org/10.1177/1084713806298004

Field, A. (2013). Discovering statistics using IBM SPSS statistics. In *Statistics* (Vol. 58).

Firszt, J. B., Holden, L. K., Reeder, R. M., Waltzman, S. B., & Arndt, S. (2012). Auditory abilities after cochlear implantation in adults with unilateral deafness: a pilot study. *Otology & Neurotology : Official Publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, *33*(8), 1339–1346. https://doi.org/10.1097/MAO.0b013e318268d52d

Friesen, L. M., & Picton, T. W. (2010). A method for removing cochlear implant artifact. *Hearing Research*, *259*(1–2), 95–106. https://doi.org/10.1016/j.heares.2009.10.012

Gartrell, B. C., Jones, H. G., Kan, A., Buhr-Lawler, M., Gubbels, S. P., & Litovsky, R. Y. (2014). Investigating long-term effects of cochlear implantation in single-sided deafness: A best practice model for longitudinal assessment of spatial hearing abilities and tinnitus handicap. *Otology and Neurotology*, *35*(9), 1525–1532.

https://doi.org/10.1097/MAO.0000000000000437

Gilley, P. M., Sharma, A., Dorman, M., Finley, C. C., Panch, A. S., & Martin, K. (2006). Minimization of cochlear implant stimulus artifact in cortical auditory evoked potentials. *Clinical Neurophysiology*, *117*(8), 1772–1782. https://doi.org/10.1016/j.clinph.2006.04.018

Gordon-Salant, S., & Fitzgibbons, P. J. (1997). Selected cognitive factors and speech recognition performance. *Journal of Speech, Language, and Hearing Research*, *40*(2), 423–431. https://doi.org/10.1044/jslhr.4002.423

Grantham, D. W., Ashmead, D. H., Haynes, D. S., Hornsby, B. W. Y., Labadie, R. F., & Ricketts, T. A. (2012). Horizontal plane localization in single-sided deaf adults fitted with a bone-anchored hearing aid (Baha). *Ear and Hearing*, *33*(5), 595–603. https://doi.org/10.1097/AUD.0b013e3182503e5e

Härkönen, K., Kivekäs, I., Rautiainen, M., Kotti, V., Sivonen, V., & Vasama, J. P. (2015). Single-Sided Deafness: The Effect of Cochlear Implantation on Quality of Life, Quality of Hearing, and Working Performance. *Orl*, *77*(6), 339–345. https://doi.org/10.1159/000439176

Hawley, M. L., Litovsky, R. Y., & Culling, J. F. (2004). The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1639908

Holland, M. K., & Tarlow, G. (1972). Blinking and mental load. *Psychological Reports*. https://doi.org/10.2466/pr0.1972.31.1.119

Holland, M. K., & Tarlow, G. (1975). Blinking and thinking. *Perceptual and Motor Skills*, *41*(2), 503–506. https://doi.org/10.2466/pms.1975.41.2.403

Hughes, S. E., Hutchings, H. A., Rapport, F. L., McMahon, C. M., & Boisvert, I. (2018). Social connectedness and perceived listening effort in adult cochlear implant users: A grounded theory to establish content validity for a new patient-reported outcome measure. *Ear and Hearing*, *39*(5), 922–934. https://doi.org/10.1097/AUD.0000000000000553

IEEE Recommended Practice for Speech Quality Measurements. (1969). *IEEE Transactions on Audio and Electroacoustics*, *17*(3), 225–246. https://doi.org/10.1109/TAU.1969.1162058

Koelewijn, T., Zekveld, A. A., Festen, J. M., & Kramer, S. E. (2012). Pupil dilation uncovers extra listening effort in the presence of a single-talker masker. *Ear and Hearing*, *33*(2), 291–300. https://doi.org/10.1097/AUD.0b013e3182310019

Kramer, S. E., Teunissen, C. E., & Zekveld, A. A. (2016). Cortisol, chromogranin A, and pupillary responses evoked by speech recognition tasks in normally hearing and hard-of-hearing listeners: A pilot study. *Ear and Hearing*, *37*, 126S-135S. https://doi.org/10.1097/AUD.0000000000000311

Litovsky, R. Y., Moua, K., Godar, S., Kan, A., Misurelli, S. M., & Lee, D. J. (2019). Restoration of spatial hearing in adult cochlear implant users with single-sided deafness. *Hearing Research*, *372*, 69–79. https://doi.org/10.1016/j.heares.2018.04.004

Litovsky, R. Y., Parkinson, A., & Arcaroli, J. (2009). Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*, *30*(4), 419–431. https://doi.org/10.1097/AUD.0b013e3181a165be

McGarrigle, R., Munro, K. J., Dawes, P., Stewart, A. J., Moore, D. R., Barry, J. G., & Amitay, S. (2014). Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group "white paper." *International Journal of Audiology*, Vol. 53, pp. 433–445. https://doi.org/10.3109/14992027.2014.890296

Mertens, G., De Bodt, M., & Van de Heyning, P. (2016). Cochlear implantation as a long-term treatment for ipsilateral incapacitating tinnitus in subjects with unilateral hearing loss up to 10 years. *Hearing Research*, *331*, 1–6. https://doi.org/10.1016/j.heares.2015.09.016

Moore, B. C. J. (2003). An Introduction to the Psychology of Hearing. *Boston Academic Press*. https://doi.org/10.1016/j.tins.2007.05.005

Ohlenforst, B., Zekveld, A. A., Lunner, T., Wendt, D., Naylor, G., Wang, Y., … Kramer, S. E. (2017). Impact of stimulus-related factors and hearing impairment on listening effort as indicated by pupil dilation. *Hearing Research*, *351*, 68–79. https://doi.org/10.1016/j.heares.2017.05.012

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., … Wingfield, A. (2016). Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL). *Ear and Hearing*, *37*, 5S-27S. https://doi.org/10.1097/AUD.0000000000000312

Piquado, T., Isaacowitz, D., & Wingfield, A. (2010). Pupillometry as a measure of cognitive effort in younger and older adults. *Psychophysiology*, *47*(3), 560–569. https://doi.org/10.1111/j.1469-8986.2009.00947.x

Privitera, C. M., Renninger, L. W., Carney, T., Klein, S., & Aguilar, M. (2010). Pupil dilation during visual target detection. *Journal of Vision*, *10*(10). https://doi.org/10.1167/10.10.3

Recarte, M. Á., Pérez, E., Conchillo, Á., & Nunes, L. M. (2008). Mental Workload and Visual Impairment: Differences between Pupil, Blink, and Subjective Rating. *The Spanish Journal of Psychology*. https://doi.org/10.1017/s1138741600004406

Recarte, M. Á., Pérez, E., Conchillo, Á., & Nunes, L. M. (2019). Mental Workload and Visual Impairment: Differences between Pupil, Blink, and Subjective Rating. *The Spanish Journal of Psychology Copyright*, *11*(2), 374–385. https://doi.org/10.1017/S1138741600004406

Rothpletz, A. M., Wightman, F. L., & Kistler, D. J. (2012). Informational masking and spatial hearing in listeners with and without unilateral hearing loss. *Journal of Speech, Language, and Hearing Research*, *55*(2), 511–531. https://doi.org/10.1044/1092-4388(2011/10-0205)

Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society*, Vol. 16, pp. 754–760. https://doi.org/10.1017/S1355617710000706

Spahr, A. J., Dorman, M. F., Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., … Cook, S. (2012). Development and validation of the azbio sentence lists. *Ear and Hearing*, *33*(1), 112–117. https://doi.org/10.1097/AUD.0b013e31822c2549

Stephens, D., & Hétu, R. (1991). Impairment, disability and handicap in audiology: Towards a consensus. *International Journal of Audiology*, Vol. 30, pp. 185–200. https://doi.org/10.3109/00206099109072885

Stern, J. A., Walrath, L. C., & Goldstein, R. (1984). The Endogenous Eyeblink. *Psychophysiology*, *21*(1), 22–33. https://doi.org/10.1111/j.1469-8986.1984.tb02312.x

Studebaker, G. A. (1985). A “rationalized” arcsine transform. *Journal of Speech and Hearing Research*, *28*(3), 455–462. https://doi.org/10.1044/jshr.2803.455

Tanaka, Y., & Yamaoka, K. (1993). Blink activity and task difficulty. *Perceptual and Motor Skills*, *77*(1), 55–66. https://doi.org/10.2466/pms.1993.77.1.55

Távora-Vieira, D., Marino, R., Krishnaswamy, J., Kuthbutheen, J., & Rajan, G. P. (2013). Cochlear implantation for unilateral deafness with and without tinnitus: A case series. *Laryngoscope*, *123*(5), 1251–1255. https://doi.org/10.1002/lary.23764

Távora-Vieira, D., Rajan, G. P., Van De Heyning, P., & Mertens, G. (2019). Evaluating the Long-Term Hearing Outcomes of Cochlear Implant Users with Single-Sided Deafness.

Otology and Neurotology, *40*(6), E575–E580. https://doi.org/10.1097/MAO.0000000000002235

Vermeire, K., & Van De Heyning, P. (2009). Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiology and Neurotology*, *14*(3), 163–171. https://doi.org/10.1159/000171478

Wagner, A. E., Nagels, L., Toffanin, P., Opie, J. M., & Başkent, D. (2019). Individual Variations in Effort: Assessing Pupillometry for the Hearing Impaired. *Trends in Hearing*, *23*. https://doi.org/10.1177/2331216519845596

Wingfield, A., & Grossman, M. (2006). Language and the aging brain: Patterns of neural compensation revealed by functional brain imaging. *Journal of Neurophysiology*, Vol. 96, pp. 2830–2839. https://doi.org/10.1152/jn.00628.2006

Winn, M. B., Edwards, J. R., & Litovsky, R. Y. (2015). The Impact of Auditory Spectral Resolution on Listening Effort Revealed by Pupil Dilation. *Ear and Hearing*, *36*(4), e153-65. https://doi.org/10.1097/AUD.0000000000000145

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best Practices and Advice for Using Pupillometry to Measure Listening Effort: An Introduction for Those Who Want to Get Started. *Trends in Hearing*, Vol. 22. https://doi.org/10.1177/2331216518800869

Wood, J. G., & Hassett, J. (1983). Eyeblinking During Problem Solving: The Effect of Problem Difficulty and Internally vs Externally Directed Attention. *Psychophysiology*, *20*(1), 18–20. https://doi.org/10.1111/j.1469-8986.1983.tb00893.x

Zeitler, D. M., Dorman, M. F., Natale, S. J., Loiselle, L., Yost, W. A., & Gifford, R. H. (2015). Sound source localization and speech understanding in complex listening environments by single-sided deaf listeners after cochlear implantation. *Otology and Neurotology*, *36*(9), 1467–1471. https://doi.org/10.1097/MAO.0000000000000841

Zekveld, A. A., Koelewijn, T., & Kramer, S. E. (2018). The Pupil Dilation Response to Auditory Stimuli: Current State of Knowledge. *Trends in Hearing*, Vol. 22. https://doi.org/10.1177/2331216518777174

Zekveld, A. A., & Kramer, S. E. (2014). Cognitive processing load across a wide range of listening conditions: Insights from pupillometry. *Psychophysiology*, *51*(3), 277–284. https://doi.org/10.1111/psyp.12151

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2010). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. *Ear and Hearing*, *31*(4), 480–490. https://doi.org/10.1097/AUD.0b013e3181d4f251

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2011). Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. *Ear & Hearing*, *32*(4), 498–510. https://doi.org/10.1097/AUD.0b013e31820512bb

Zheng, B., Jiang, X., Tien, G., Meneghetti, A., Panton, O. N. M., & Atkins, M. S. (2012). Workload assessment of surgeons: Correlation between NASA TLX and blinks. *Surgical Endoscopy*, *26*(10), 2746–2750. https://doi.org/10.1007/s00464-012-2268-6

CHAPTER III. Investigating the Relationship Between Asymmetric Speech Intelligibility and Listening Effort in Adults with Bilateral Cochlear Implants

I. Abstract

Bilateral cochlear implants (BiCIs) facilitate improved speech intelligibility in noise and sound localization abilities compared to a unilateral implant. Nevertheless, individuals with BiCIs frequently demonstrate asymmetry, with one ear outperforming the other on measures of speech intelligibility. It is yet to be determined how the better- and poorer-ear individually impact the amount of effort experienced by BiCI users. Elevated listening effort is a common report of patients with hearing loss and is associated with adverse psycho-social outcomes. Thus, this is an important aspect of communication to investigate, but is not captured by a single performance measure such as a speech intelligibility score. The measure of pupil dilation (pupillometry) can be used to objectively quantify listening effort and task engagement during listening tasks. Large pupil sizes indicate a high amount of effort and engagement in the task, and small pupil sizes indicate low effort and engagement. We used pupillometry to investigate the effect of bilateral listening (as compared to better-ear listening) on speech intelligbilty and listenging effort in 12 adults with BiCIs. Participants were tested in three conditions: with their better ear only, poorer ear only, and bilaterally. Female-talker IEEE sentences were presented from a loudspeaker at 0° azimuth in quiet while changes in pupil dilation were measured. Verbal responses were scored by an experimenter. Results revealed substantial variability in speech intelligibility both within and across participants. Within participipnats, the difference between ears varied from 1% to 57%. Participants performed significantly worse in the Poorer Ear condition, and similarly in the Better ear and Bilateral conditions. Pupil dilation was smallest for the Better Ear condition, and largest for Poorer Ear and Bilateral conditions. Despite performing similarly in the Better Ear and Bilateral conditions on the speech intelligibility measure, pupil dilation was significantly larger for the Bilateral condition, suggesting that the addition of the

Poorer Ear elicited an increase in listening effort. Due to the great deal of inter-subject variability, this increase in pupil dilation likely reflects processes unique to individuals. Participants were divided into Symmetric and Asymmetric groups depending on whether the degree of interaural speech asymmetry was statistically significant. For both the Symmetric and Asymmetric groups, there were no significant differences in speech intelligibility between Better Ear and Bilateral conditions, and there were no significant differences in pupil dilation between Poorer Ear, Better Ear, and Bilateral conditions. This indicates that degree of interaural asymmetry is not sufficient to predict changes to listening effort from better-ear to bilateral listening in BiCI users.

II. Introduction

Human communication is complex and multifaceted, and cannot be fully appreciated by a single performance measure such as a speech intelligibility score. For example, successful communication also requires mental resources, including engagement of attentional mechanisms and listening effort. The degree of mental resources allocated can vary depending on the environment (e.g., quiet versus noisy environments). Listening effort is defined as the intentional focus of cognitive resources to perform listening tasks (Pichora-Fuller et al., 2016). The amount of effort a listener expends is thought to be influenced by their motivation to perform the task (S. E. Hughes, Hutchings, Rapport, McMahon, & Boisvert, 2018; Pichora-Fuller et al., 2016). Thus, two individuals listening to the same conversation may exert different amounts of effort depending on how motivated they are to pay attention and understand what is being said (Winn, Wendt, Koelewijn, & Kuchinsky, 2018). Listening effort is an important aspect of communication to investigate because elevated effort is associated with fatigue and stress, especially for individuals who must overcome additional listening obstacles like hearing loss. In fact, studies have found that individuals with hearing loss report higher levels of effort and fatigue, are more likely to require recovery after work, and are more likely to take sick-leave due to stress-related factors compared to normal hearing (NH) individuals (Alhanbali, Dawes, Lloyd, & Munro, 2017; Kramer, 2008; Kramer, Kapteyn, & Houtgast, 2006; Nachtegaal et al., 2009). Additionally, the perceived requirement to exert elevated effort in complex listening situations has been associated with feelings of social isolation and anxiety in individuals with hearing loss (S. E. Hughes et al., 2018).

Individuals with severe-to-profound hearing loss who do not benefit from a hearing aid can receive a cochlear implant (CI). An increasing number of patients with bilateral hearing loss are now being bilaterally implanted, for numerous reasons, including improvement in sound localization and speech understanding, both in quiet and in noisy environments. Compared to hearing aids or a unilateral implant, most individuals with bilateral CIs (BiCIs) have been shown to demonstrate improvements in spatial hearing abilities, including sound localization (e.g., Gantz et al., 2002; Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Laszig et al., 2004; Litovsky, Parkinson, & Arcaroli, 2009; Litovsky et al., 2004; Nopp, Schleich, & D'Haese, 2004; Tyler, Dunn, Witt, & Noble, 2007; van Hoesel & Tyler, 2003) and speech understanding in noise (e.g., Gantz et al., 2002; Litovsky et al., 2009, 2004; Loizou et al., 2009; Nopp et al., 2004; Schleich, Nopp, & D'Haese, 2004; Tyler et al., 2007; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel & Tyler, 2003). With regard to speech intelligibility in quiet, results have been mixed. NH listeners experience a binaural benefit known as binaural summation or redundancy when listening with two ears versus one. This benefit is derived from having access to duplicate copies of the signal, and an increase in perceptual loudness (Avan, Giraudet, & Büki, 2015). Some studies have shown that BiCI users can obtain a similar benefit from bilateral listening compared to unilateral listening in quiet. For example, Mosnier et al. (2009) found a binaural benefit of 10% in quiet for BiCI listeners using disyllabic word stimuli. Similarly, BiCI users in Laszig et al. (2004) demonstrated a binaural benefit of 4% using open-set sentence stimuli. In contrast, the same group of listeners in Laszig et al. (2004) did not show a significant binaural benefit using a different open-set sentence corpus, and BiCI users in Goupell et al. (2018) also did not demonstrate a binaural benefit using the IEEE sentence corpus. At least some of this variability in binaural benefit in quiet appears to related to interaural asymmetry. When Mosnier et al. (2009) split listeners into symmetric and asymmetric groups based on the difference in speech scores across ears, symmetric listeners (< 20% difference in percent correct across ears), demonstrated a significant amount of binaural redundancy, whereas asymmetric listeners did not. Likewise, listeners in Goupell et al. (2018) were recruited based on their asymmetric hearing history or early onset of deafness, suggesting that interaural asymmetry may preclude binaural redundancy benefits in quiet. In fact, previous work has found that BiCI listeners with small asymmetries in speech intelligibility perform best when listening bilaterally compared to either ear alone, and that individuals with large asymmetries might perform best when listening with only their better ear (Bernstein, Goupell, Schuchman, Rivera, & Brungart, 2016; Goupell et al., 2018; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006; Mosnier et al., 2009).

While the performance benefits have been widely examined, there has been less attention given to the potential effort-related benefits of BiCIs. One study administered the Abbreviated Profile of Hearing Aid Benefit questionnaire to BiCI users during a “bilateral deprivation” period in which patients only wore the CI of their better performing ear, and again several months later after patients had access to both of their CIs. They found that patients perceived bilateral listening to be beneficial when listening in background noise and reverberant environments, and found bilateral listening to be “easier” than unilateral listening (Litovsky et al., 2006). Another study employed the Speech, Spatial, and Qualities of Hearing Scale, and found that the use of two CIs yielded higher ability ratings on the spatial hearing domain, as well as segregation, naturalness, and listening effort aspects (Noble, Tyler, Dunn, & Bhullar, 2008). While there is some subjective evidence that BiCIs may reduce listening effort compared to a unilateral CI, only one study to date has studied this objectively. Hughes and Galvin (2013) employed a dual-task paradigm to objectively measure listening effort in BiCI users in bilateral and unilateral listening conditions, and found that three out of eight BiCI users demonstrated a reduction in listening effort when using two implants compared to one (K. C. Hughes & Galvin, 2013).

Due to the limited knowledge on listening effort in individuals with BiCIs, this study aimed to investigate speech intelligibility and listening effort in this patient population. We employed pupillometry, i.e., the measure of pupil dilation, to quantify listening effort in unilateral and bilateral listening conditions. Pupil dilation is modulated by cognitive load, increasing for difficult tasks that require more processing demand, and decreasing for tasks that are less challenging (Beatty, 1982). When the task becomes so difficult that listeners may feel that additional effort would not benefit performance, motivation declines and pupil dilation also decreases (Ohlenforst et al., 2017; Pichora-Fuller et al., 2016). This effect has been shown for listening tasks that measure speech intelligibility. Pupil dilation increases as performance decreases to ~30% correct, after which pupil dilation then decreases, presumably due to a decline in motivation and engagement (Ohlenforst et al., 2017; Wendt, Koelewijn, Książek, Kramer, & Lunner, 2018). Compared to other physiological measures that can be used to measure listening effort, (e.g., functional magnetic resonance imaging, electroencephalography), pupillometry has the advantage of being compatible with assistive devices like hearing aids and CIs (Friesen & Picton, 2010; Gilley et al., 2006; Wagner, Nagels, Toffanin, Opie, & Başkent, 2019). Additionally, unlike a dual-task paradigm, which relies on a single metric such as response time (Gagné, Besser, & Lemke, 2017), pupil dilation can be measured during a behavioral listening task in order to capture mental effort as it unfolds over time (Winn et al., 2018). Examining speech intelligibility and listening effort in BiCI users in unilateral and bilateral listening conditions will allow us to investigate the potential benefits of bilateral listening in both performance and effort domains, both of which are important for successful communication.

The purpose of this study was to investigate speech intelligibility and listening effort in adults with BiCIs in three conditions: with their poorer ear only, better ear only, and bilaterally.

Based on previous work that has found increased speech intelligibility in quiet (Laszig et al., 2004; Mosnier et al., 2009), and a reduction in listening effort for bilateral compared to unilateral listening (K. C. Hughes & Galvin, 2013; Litovsky et al., 2006; Noble et al., 2008), we predicted that speech intelligibility would be better, and pupil dilation would be smaller, for BiCI users listening with both implants compared to their better ear implant only. Additonally, due to the potential relationship between interaural asymmetry and bilateral performance, a secondary analysis aimed to examine differences in binaural benefit between symmetric and asymmetric listeners. Interaural asymmetry has been found to significantly affect patient's perceived hearing disability for spatial hearing, sound naturalness and clarity, signal segregation, and effort of conversation (Gatehouse & Noble, 2004), so it is possible that asymmetric listeners may demonstrate an increase in listening effort from better ear to bilateral listening due to differences in the fidelity of signals across ears, which could make the task more difficult.

III. Methods

A. Participants

Twelve native English-speaking adults with BiCIs were recruited to participate in this experiment (age range 25-78 years). Table 1 provides demographic information for each participant. Participants traveled to Madison, Wisconsin for the study, and testing took place over the course of one 2-hour session. This study was approved by the University of Wisconsin-Madison Health Sciences Institutional Review Board.

B. Experimental Setup

Testing was conducted in a standard sound booth. Participants sat in a comfortable chair in front of a table with a fixed head mount, where they rested their chin and forehead. To ensure comfort, the height of the table and/or chair was adjusted for each participant. A computer monitor was attached to the table via an adjustable arm and was positioned so that it was approximately 65 cm away from the headrest. Illumination of the test room was set to 93 lux for all participants. The computer monitor background was set to a neutral color (medium gray) to avoid excessive pupil constriction or discomfort (Winn et al., 2018). A loudspeaker (Tannoy, Coatbridge, Scotland) was positioned at 0° azimuth at a height of 130 cm. Pupil size was measured in pixels using the "Area" setting on an eyetracker (Eyelink 1000 Plus). Pupil area was sampled at a rate of 1000 Hz using a proprietary algorithm developed by Eyelink manufacturers. The eyetracker camera was fixed to the table via a desktop mount 8 cm in front of the computer monitor.

C. Stimuli

Stimuli were drawn from the Institute of Electrical and Electronics Engineers open-set sentence corpus ("IEEE Recommended Practice for Speech Quality Measurements," 1969) and were recorded by a female talker. Prior to testing, all stimuli were equalized to 85 dB sound pressure level (SPL)-A and stored as .wav files. During testing, stimuli were scaled to 65 dB SPL-A and played to the loudspeaker through a USB high-speed audio interface (RME Fireface, Haimhausen, Germany). Target sentences ranged from 4,000 to 6,000 ms in duration. A computer with customized software written in MATLAB (The MathWorks, Natick, MA) was used to deliver stimuli and collect data.

D. Procedure

Participants were tested in three listening conditions: better-ear only, poorer-ear only, and bilateral (Table 2). Prior to testing, the better ear was classified as the ear with the higher word recognition score measured in the audiology clinic. If there was no difference in word recognition scores between the two ears, the participant's preferred ear according to subjective reporting was labeled the "better" ear. Before beginning the experiment, an interaural loudness balance check was completed to verify that both CIs were perceived as equally loud. Participants completed a familiarization procedure in which they listened to and repeated 10 sentences in each condition. Stimuli for practice trials were randomly selected and then excluded from the test corpus to avoid any sentence repetitions.

During testing, participants were asked to fixate their gaze on a small grey cross in the center of the computer screen and attend to target sentences presented directly in front of them (0° azimuth) by a loudspeaker. Participants were instructed to repeat the sentence that was heard. The trial structure and participant interface were the same as those used for the experiment presented in Chapter II. At the beginning of each trial, the cross turned white to indicate that the testing was about to commence. The trial began with a 1,000-ms baseline pupil recording in silence before the stimulus was presented. Following the stimulus offset, there was a 2,000-ms silent period to allow participants to think and prepare to respond. The cross on the screen then turned green and the participant heard two beeps, prompting them to repeat what they heard (Chapter II-Figure 1). Each sentence contained five key words that were scored by an experimenter. The experimenter waited 10 to 15 s between trials to allow the pupil to return to baseline before beginning the next trial. Frequent breaks were given throughout testing to avoid fatigue.

Thirty trials were blocked into two runs of 15 sentences per listening condition. The order of conditions was randomized for each participant, and for each run, target stimuli were randomly selected from the corpus without replacement. All trials were averaged into a single pupil track for each condition and trials with significant artifacts were discarded from analysis (Winn et al., 2018). Listening effort was quantified by measuring peak pupil dilation during the silent period (reported as proportion change from baseline), where larger dilation was interpreted as greater task engagement or cognitive load.

E. Data Analysis

Pupil tracks with greater than 45% blinks were discarded from analysis. This blink criterion was chosen because it is more inclusive compared to other commonly used criteria (e.g., 15%, 30%). Previous work has shown an association between task difficulty and blink rate or blink percentage, which could result in a higher number of difficult tries being excluded from analysis, potentially confounding results (Burg et al., 2021). When calculating the percentage of missing samples in a track, only samples from the onset of the baseline to the end of the silent period were considered. The response period was not included in the analysis because this part of the pupil track is influenced by the motor response and is therefore not purely related to task difficulty (Privitera, Renninger, Carney, Klein, & Aguilar, 2010; Winn, Edwards, & Litovsky, 2015). Consistent with methods for excluding contaminated trials from analysis, as described by Winn et al. (2018), tracks with vastly irregular baseline measurements, excessive distortions during the stimulus or silent period, or disproportionately large growth that is not typical of task-evoked changes in pupil dilation were also discarded. Further, tracks that contained a large section of missing data in a region of interest (e.g., during the silent period from which maximum pupil dilation is extracted) were also discarded, as the interpolation could flatten the peak of the pupil response.

In addition to discarding contaminated trials and processing the data using the specified blink criterion, the data for each condition were “de-blinked” (i.e., linearly interpolated between gaps of missing data) and low-pass filtered with a 10-ms time window using the “smooth” function in MATLAB. Methods for detecting blinks are in accordance with those described by Zekveld et al. (2010), where pupil dilations that fell below three standard deviations (SDs) from the mean were tagged as missing samples. The segments of missing data were linearly interpolated 80 ms before the blink and 160 ms following the blink to account for disturbances in pupil size caused by the eyelid opening and closing (Zekveld et al., 2010). Tracks were then baseline corrected by subtracting the baseline value (calculated by averaging the pupil response measured 1,000 ms before stimulus onset) and then dividing by the baseline value to obtain the proportion of pupil change from baseline. Finally, tracks were time-aligned to stimulus offset and averaged together by condition for each participant.

Both maximum pupil dilation (i.e., maximum proportional change from baseline) and percentage of correctly repeated words were calculated for all included trials. Maximum pupil dilation was extracted from the 2,000 ms after the stimulus offset and before the response prompt, classified as the “silent period” (Figure 1). This period is considered to be a window where listeners process and plan their response (Zekveld et al., 2010). While the latency for peak pupil dilation can vary across participants, this window has commonly been shown to elicit the greatest amount of pupil dilation throughout the trial for sentence-recognition tasks such as the one used here (Winn et al., 2015, 2018).

F. *Statistical Analysis*

First, the effects of listening condition on speech intelligibility and listening effort were evaluated using two separate one-way repeated measure analysis of variance (ANOVA) tests with listening condition (three levels: Better Ear, Poorer Ear, Bilateral) as the independent variable. For these ANOVAs, dependent variables were either speech intelligibility (percent of words correctly repeated) or proportional change in pupil dilation (maximum pupil size during the silent period). Assumptions for omnibus and post-hoc tests were statistically evaluated using Mauchly’s Test of Sphericity and Shapiro-Wilk normality tests. Post-hoc pairwise comparisons were completed with paired t-tests for normally distributed data, and Wilcoxon Signed Rank tests for non-normally distributed data. Benjamini-Hochberg corrections were employed to control false discovery rate (Benjamini & Hochberg, 1995).

In a second analysis, participants were split into two groups to classify them as either ‘Symmetric’ or ‘Asymmetric.’ 95% confidence intervals were compared for each participant’s Better and Poorer ear speech intelligibility scores using the binomial distribution (95% confidence interval = mean ± 1.96*standard error (SE)). Participants with overlapping confidence intervals were classified as Symmetric, and those with non-overlapping confidence intervals were classified as Asymmetric. In two separate mixed-effect ANOVAs, listening condition (within-subjects factor with three levels: Better Ear, Poorer Ear, Bilateral) and group (between-subjects factor with two levels: Symmetric, Asymmetric) were treated as the independent variables, and either speech intelligibility or proportional change in pupil dilation was treated as the dependent variable. Assumptions for omnibus and post-hoc tests were statistically evaluated using the Shapiro-Wilk normality test and Mauchly’s Test of Sphericity. Post-hoc pairwise comparisons for within-subjects variables were completed with paired t-tests for normally distributed data, and Wilcoxon Signed Rank tests for non-normally distributed data. Pairwise comparisons for between-subjects variables were completed using independent samples t-tests for normally distributed data or Wilcoxon Rank Sum tests for non-normally distributed data. Benjamini-Hochberg corrections were employed to control false discovery rate (Benjamini & Hochberg, 1995). An alpha of 0.05 was used to determine whether results were significantly different from chance.

IV. Results

Mean speech intelligibility for each listening condition is shown in Figure 2 (open circles). Speech intelligibility was higher for the Better Ear and Bilateral conditions (Better Ear mean ± SD = 80.2% ± 21.9; Bilateral mean = 80.7 ± 23.7) than the Poorer Ear condition (mean = 61.5% ± 32.4), and there was substantial inter-subject variability in performance. A one-way repeated measures ANOVA using a Greenhouse-Geisser correction revealed a significant main effect of listening condition on percent correct score [$F(2,22)=10.6$, $p<0.05$]. Post-hoc pairwise comparisons revealed that percent correct score was significantly worse for the Poorer Ear condition compared to the Better Ear ($p<0.01$) and Bilateral conditions ($p<0.01$). This indicates that, on average, the BiCI users in our study had significant speech performance asymmetry across ears, but this asymmetry did not significantly affect performance in the Bilateral condition compared to the Better Ear condition. This is not surprising considering listeners were tested in quiet, and could rely on their better ear for speech performance.

Mean pupil tracks for each condition are shown in Figure 1. If we examine the entire duration of the silent period (0-2000 ms) pupil dilation appears to be largest for the Poorer Ear condition, followed by the Bilateral condition, and finally the Better Ear condition. Maximum pupil dilation was extracted from this period and is plotted in Figure 2 (filled circles). Maximum pupil dilation was smallest for the Better Ear condition (mean = 0.23 ± 0.15), and similar for Poorer Ear and Bilateral conditions (Poorer Ear mean = 0.27 ± 0.12; Bilateral mean = 0.28 ± 0.15). A one-way repeated measures ANOVA revealed that the main effect of listening condition was not significant [$F(2,22)=2.4$, $p=0.1$]. An omnibus test takes all comparisons into account, meaning that it is less likely to identify a significant difference between one pair of conditions if all other pairwise comparisons are non-significant. Given our predictions regarding differences in pupil dilation across conditions, post-hoc tests were completed in order to investigate whether our small sample size and the substantial amount of inter-subject variability negatively affected the power of the omnibus test. Results revealed that pupil dilation was significantly larger in the Bilateral condition than the Better Ear condition ($p<0.05$). There were no significant differences between the Poorer Ear and Better Ear, or Poorer Ear and Bilateral conditions.

A. *Comparison of Symmetric and Asymmetric Listeners*

In order to examine the effect of speech asymmetry on bilateral speech intelligibility and listening effort, percent correct scores for each participant's poorer and better ear were compared. We found that six participants had significant differences in speech intelligibility across ears (Asymmetric Group), and six did not (Symmetric Group-Table 1). Three listeners in the Asymmetric group had asymmetries greater than 40% across ears, while the other three demonstrated relatively smaller asymmetries, on the order of ~15%. Asymmetries in the Symmetric group ranged from ~1-10%. Mosnier et al. (2009) used a criterion of 20% to classify listeners with significant across-ear asymmetries. Similarly, Goupell et al. (2018) reported that all listeners with significant differences in across-ear performance had greater than 20%

asymmetry. Thus, our Asymmetric group included listeners with smaller across-ear differences than previous studies. This was a by-product of including all BiCI listeners who were able to participate in the experiment, and evaluating their asymmetries in a retrospective analysis. Mean speech intelligibility for both groups is plotted in Figure 3A and stated in Table 2. On average, speech intelligibility for the Asymmetric group was worse for all conditions compared to the Symmetric group, and variability for the Asymmetric group was much greater. Speech intelligibility for the Symmetric group increased from the Better Ear to the Bilateral condition (ΔPC = 3.8% ± 4.5), indicating that the addition of the poorer ear may have been beneficial. In contrast, speech intelligibility for the Asymmetric group decreased from the Better Ear to Bilateral condition (ΔPC = -3.0 % ± 8.2), suggesting that the poorer ear may have interfered with speech intelligibility. A mixed-effect ANOVA using a Greenhouse-Geisser correction revealed a significant main effect of listening condition [$F(2,20)=18.5$, $p<0.001$], and a significant interaction between group and listening condition [$F(2,20)=9.1$, $p<0.05$]. The main effect of group was not significant [$F(1,10)=7.9$, $p=0.08$]. Post-hoc pairwise comparisons for the Asymmetric group indicated that speech intelligibility in the Better Ear and Bilateral conditions was significantly higher than the Poorer ear [Better Ear: $p<0.05$; Bilateral: $p<0.05$]. The difference between Better Ear and Bilateral performance was not significant ($p=0.4$). Post-hoc testing for the Symmetric group revealed that speech intelligibility did not differ significantly for any of the listening conditions ($p>0.05$ for all comparisons). Across-group comparisons within each condition indicated that speech intelligibility was significantly worse in the Poorer Ear condition for the Asymmetric group compared to the Symmetric group ($p<0.05$). Performance in the Better Ear and Bilateral conditions did not differ significantly across groups ($p>0.05$ for both comparisons).

Mean proportional change in pupil dilation for both groups is plotted in Figure 3B and stated in Table 2. On average, pupil dilation was smaller across all conditions for the Symmetric group compared to the Asymmetric group, and there was greater variability for the Symmetric group. Both groups demonstrated similar trends across conditions, with the Better Ear condition eliciting smaller pupil dilation (Asymmetric Better mean = 0.21 ± 0.11; Symmetric Better mean = 0.25 ± 0.19) than the Poorer Ear (Asymmetric Poorer mean = 0.25 ± 0.10; Symmetric Poorer mean = 0.29 ± 0.14) and Bilateral conditions (Asymmetric Bilateral mean = 0.27 ± 0.14; Symmetric Bilateral mean = 0.29 ± 0.18). Pupil dilation for the Symmetric group increased from the Better Ear to the Bilateral condition ($\Delta PD = 0.04 \pm 0.04$). Likewise, pupil dilation for the Asymmetric group increased from the Better Ear to Bilateral condition ($\Delta PD = 0.06 \pm 0.06$), and the change was larger than that observed for the Symmetric group. Main effects of group, listening condition, and the interaction between group and listening condition were not significant. Post-hoc tests did not find any significant differences between conditions within groups, or across groups.

V. Discussion

This study measured speech intelligibility and listening effort in individuals with BiCIs in order to examine the potential benefits of bilateral listening in both performance and effort domains. Additionally, we were interested in the relationship between asymmetries in speech performance across the two ears and bilateral outcomes. Speech intelligibility was significantly worse in the Poorer Ear condition compared to the Better Ear and Bilateral conditions, and there was no significant difference between Better Ear and Bilateral performance. Interestingly, pupil dilation was significantly larger in the Bilateral compared to Better Ear condition, and there was no significant difference between the Better Ear and Poorer Ear condition. This suggests that, on average, the BiCI users tested in this study did not obtain a performance benefit from binaural redundancy, nor did they obtain a release from effort when listening with two ears versus their better ear only.

The lack of measurable binaural benefit in the present study is in contrast to BiCI users tested in a study by Mosnier et al. (2009) using disyllabic word stimuli. They found that BiCI users obtained a significant improvement of 10% in quiet using both implants compared to their better ear implant only. However, their BiCI participants were selected to fit specific criteria with regard to preoperative performance, duration of hearing loss, and difference in duration of deafness across ears. Additionally, they were simultaneously implanted, whereas listeners in our study had variable inter-implant delays ranging from 0-18 years (Mosnier et al., 2009). A study by Laszig and colleagues (2004) found a significant binaural benefit of 4% compared to better ear listening for sentences in quiet for one corpus, but did not find a binaural advantage in the same listeners using a different sentence corpus. They suggested that ceiling effects could have precluded the ability to measure a binaural advantage (Laszig et al., 2004). This may have been the case for our subjects as well, considering seven of our twelve listeners scored above 90% correct in the Better Ear condition. Their finding of a significant binaural advantage using one sentence corpus but not the other also emphasizes the influence of test materials on measuring this advantage in quiet. Further, their listeners demonstrated less interaural asymmetry, with mean difference between ears ranging from ~3-10% depending on which corpus was used, whereas our listeners demonstrated an average of 18.7% ± 20.8 asymmetry (Laszig et al., 2004). Goupell et al. (2018) measured speech intelligibility in quiet for nine BiCI listeners using the same sentence corpus as the present study (IEEE), and did not find any significant binaural advantage, which is in line with our results.

Pupil dilation is modulated by cognitive load, increasing for difficult tasks that require more processing demand, and decreasing for tasks that are less challenging (Beatty, 1982). In studies investigating pupil dilation as a function of speech intelligibility, pupil size inceases as the task becomes more difficult (e.g., as signal-to-noise ratio decreases), until a point where listeners may feel that additional effort would not benefit performance. Beyond this point, pupil dilation has been shown to decrease, reflecting a reduction in listeners' engagement in the task (Ohlenforst et al., 2017; Pichora-Fuller et al., 2016; Wendt et al., 2018; Winn et al., 2018). Our finding that pupil dilation significantly increased from the Better Ear to Bilateral listening condition cannot be explained by a change in speech intelligibility, since there was no significant difference between performance in the Better Ear and Bilateral conditions. In fact, only two subjects demonstrated significant differences in performance between Better Ear and Bilateral conditions: ICJ's performance decreased significantly (interference), and ICD's performance increased significantly (binaural redundancy), however, the corresponding change in pupil dilation was relatively small for both of these participants (Figure 4). Interestingly, the largest changes in pupil dilation from Better Ear to Bilateral conditions seemed to occur for participants whose performance was similar (IBL, ICP) or near ceiling level (ICW, IBK, IDI, IBZ) for both conditions. Considering the variability in performance of the poorer ear for these participants, several situations are possible. IBK, IDI, and IBZ performed near ceiling level for all three conditions (>85% for all participants). Since participants are used to listening with both implants in everyday life, one possibility is that bilateral listening facilitated increased engagement in the task. ICP, IBL, and ICW performed similarly for Better Ear and Bilateral conditions, but demonstrated significantly worse performance for the Poorer Ear condition (17%, 45%, and 57% difference, respectively, between the better and poorer ear). For these participants, it may be that the addition of the poorer ear was distracting and caused participants to increase effort in order to attend to clearer speech in their better ear. In summary, there was substantial variability across the BiCI users tested in this study, making it difficult to come to a single conclusion about what increased effort from Better Ear to Bilateral listening implies.

Due to the significant variability that exists across BiCI users, we reasoned that dividing listeners into two groups based on the difference in speech intelligibility across ears would enable us to draw clearer conclusions about the effect of bilateral listening on speech intelligibility and listening effort. Six participants had significant differences across ears, while the other six did not. Speech intelligibility for the Symmetric group increased (ΔPC = 3.8% ± 4.5) and intelligibility for the Asymmetric group decreased (ΔPC = -3.0 % ± 8.2) from Better Ear to Bilateral conditions. However, these differences did not reach statistical significance. Contrary to our prediction, we did not observe any significant differences in pupil dilation across conditions for either group. This may have been due ceiling effects and a lack of power due to high variability among participants and our small sample size.

In total, four listeners demonstrated interference (ICW, ICJ, ICP, ICB), defined as a decrease in performance from Better Ear to Bilateral listening. All four of these listeners belonged to the Asymmetric group, although the amount of interference was only significant for one listener (ICJ: 18% difference in speech intelligibility between the Better Ear and Bilateral conditions). This participant had the second largest interaural asymmetry (53%). Interestingly, ICJ was simultaneously implanted, and had almost 9 years of bilateral CI experience prior to testing. The participant with the largest interaural asymmetry (ICW: 57%) and the longest inter-implant delay (18.6 years) only demonstrated 2% of interference. This is prime example of the extreme variability that exists among BiCI users, and how difficult it can be to predict performance due to the vast number of variables that can contribute to performance outcomes in each ear and across ears (Gantz et al., 2002; Litovsky et al., 2006; Mosnier et al., 2009).

VI. Summary

The present study measured speech intelligibility and pupil dilation to quantify differences in performance and listening effort in adults with BiCIs when listening with their poorer ear only, better ear only, and bilaterally. Previous studies have shown that some BiCI users can benefit from binaural redundancy, and demonstrate an increase in performance from better ear to bilateral listening. BiCI users tested in this study performed similarly when listening with their better CI only and with both CIs together. Additionally, listeners exhibited an increase in pupil dilation for bilateral compared to better ear listening. Due to the great deal of inter-subject variability, this increase in pupil dilation likely reflects unique processes for individual participants. Six BiCI listeners demonstrated significant interaural asymmetries in speech intelligibility, and six did not. Within groups, there were no significant differences in speech intelligibility between Better Ear and Bilateral conditions, and there were no significant differences in pupil dilation between Poorer Ear, Better Ear, and Bilateral conditions. Thus, degree of interaural asymmetry may not be sufficient to predict changes to listening effort from better ear to bilateral listening in BiCI users.

Acknowledgements

This research was supported by NIH-NIDCD Grant No. R01DC003083 (to RYL) and NIH-NICHD Grant No. U54HD090256 (to Waisman Center). Portions of this work were presented at the 2019 American Academy of Audiology Conference, 2019 Association for Research in Otolaryngology Conference, and 2019 Conference on Implantable Auditory Prostheses. The authors would like to thank the individuals who participated in this study, and members of the Binaural Hearing and Speech Lab for assistance with participant recruitment, scheduling, and testing.

VII. Figures and Tables

Table 1

Subject ID	Age (yrs)	Better ear	Inter-implant Delay (yrs)	Bilateral CI Experience (yrs)	Group
ICW	25	Right	18.6	4.9	Asymmetric
IBZ	51	Right	1.3	11.0	Symmetric
IDI	52	Right	0.6	4.6	Symmetric
IBY	55	Right	4.2	7.3	Symmetric
ICP	56	Left	3	7.3	Asymmetric
ICD	61	Left	6.0	10.0	Symmetric
ICB	67	Left	2.8	12.9	Asymmetric
ICJ	69	Right	0.0	8.8	Asymmetric
IDG	70	Right	2.0	7.7	Symmetric
IBL	72	Right	4.8	12.8	Asymmetric
ICK	75	Left	1.0	7.2	Asymmetric
IBK	78	Left	6.0	9.8	Symmetric

Table 1. Participant demographics.

Figure 1

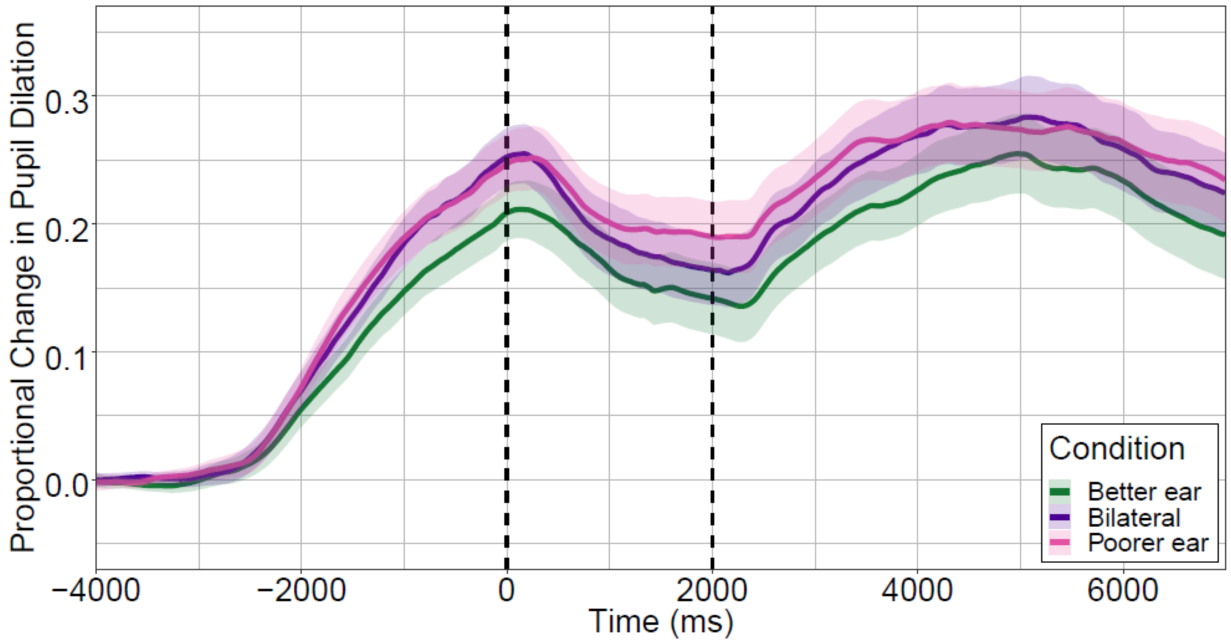


Figure 1. Mean proportional change in pupil dilation for each listening condition. Maximum proportional change in pupil dilation was extracted from the silent period, indicated by the vertical dashed lines (0-2000 ms). Shaded region represents ± 1.96 SE (95% confidence interval).

Figure 2

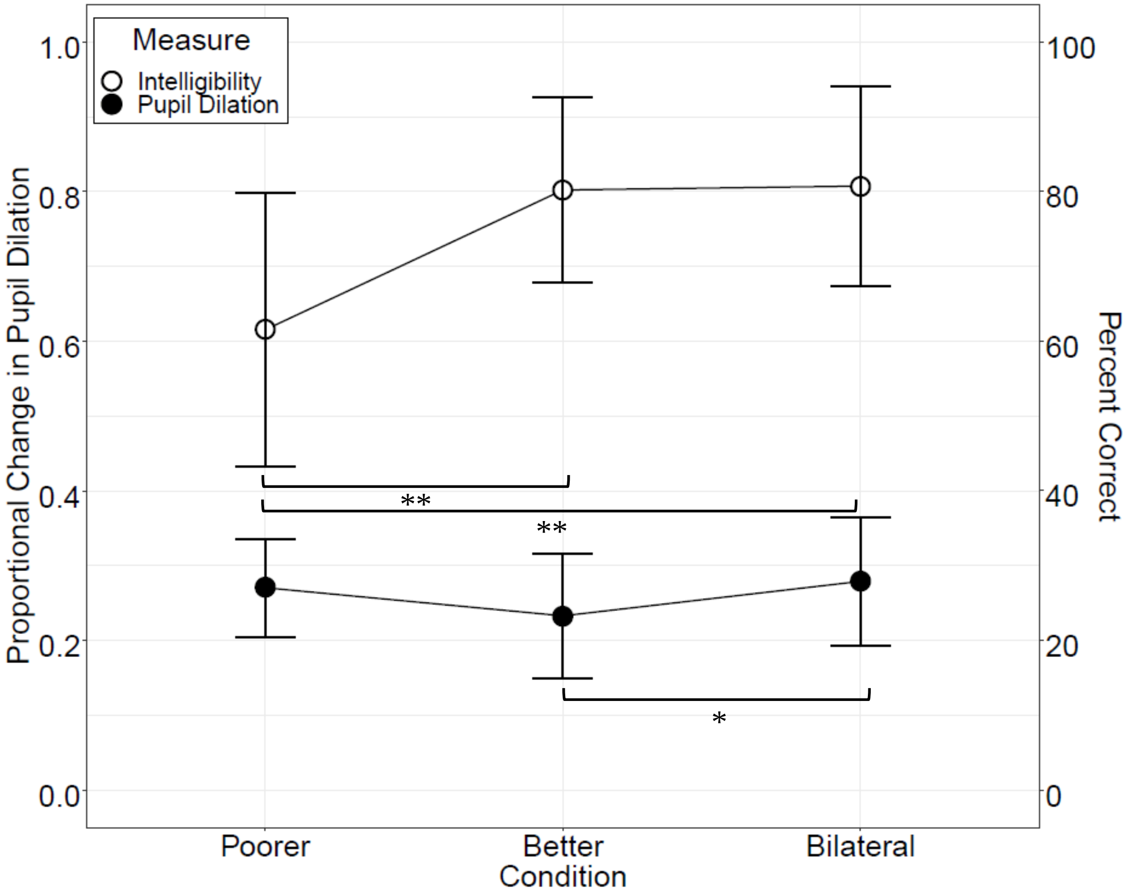


Figure 2. Mean speech intelligibility score measured as percent of correctly repeated words (unfilled circles) and mean proportional change in pupil dilation (n=12). Error bars represent ± 1.96 SE (95% confidence interval). Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 3

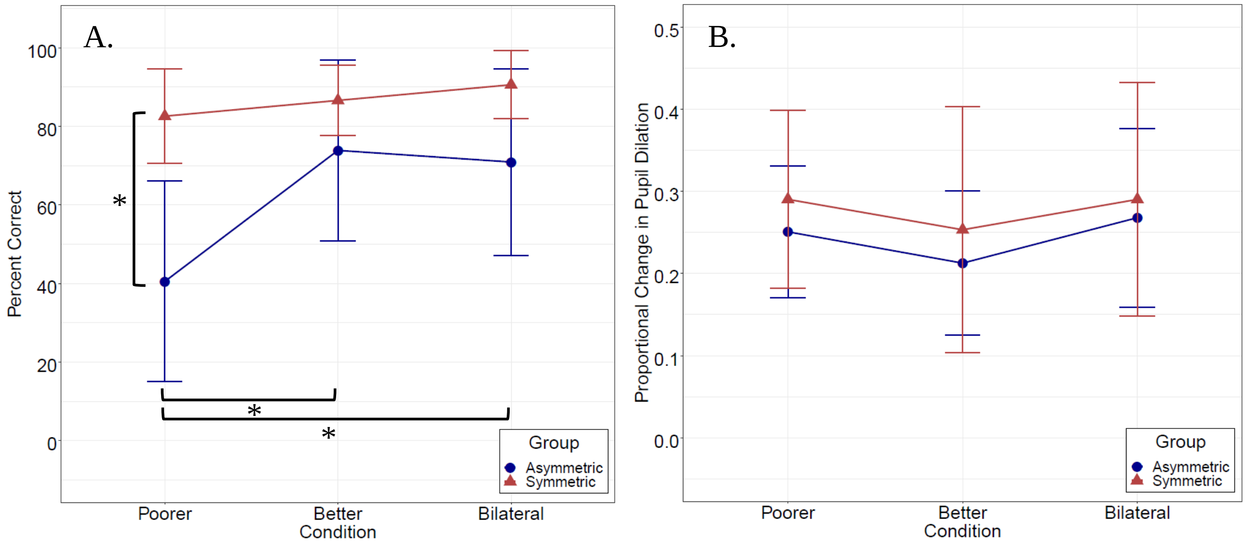


Figure 3. A) Mean speech intelligibility scores for Symmetric (n=6) and Asymmetric (n=6) listeners and B) mean proportional change in pupil dilation for Symmetric and Asymmetric listeners. Error bars represent ± 1.96 SE (95% confidence interval). Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Table 2

	Mean Speech Intelligibility ± SD			**Mean Proportional Change in Pupil Dilation ± SD**		
Group	Poorer Ear	Better Ear	Bilateral	Poorer Ear	Better Ear	Bilateral
Symmetric	82.6±15.0	86.6±11.2	90.6 ±10.9	0.29±0.14	0.25±0.19	0.29±0.18
Asymmetric	40.5±31.9	73.9±28.9	70.9 ±29.7	0.25±0.10	0.21±0.11	0.27±0.14

Table 2. Mean speech intelligibility and mean proportional change in pupil dilation for Symmetric and Asymmeric groups in each listening condition.

Figure 4

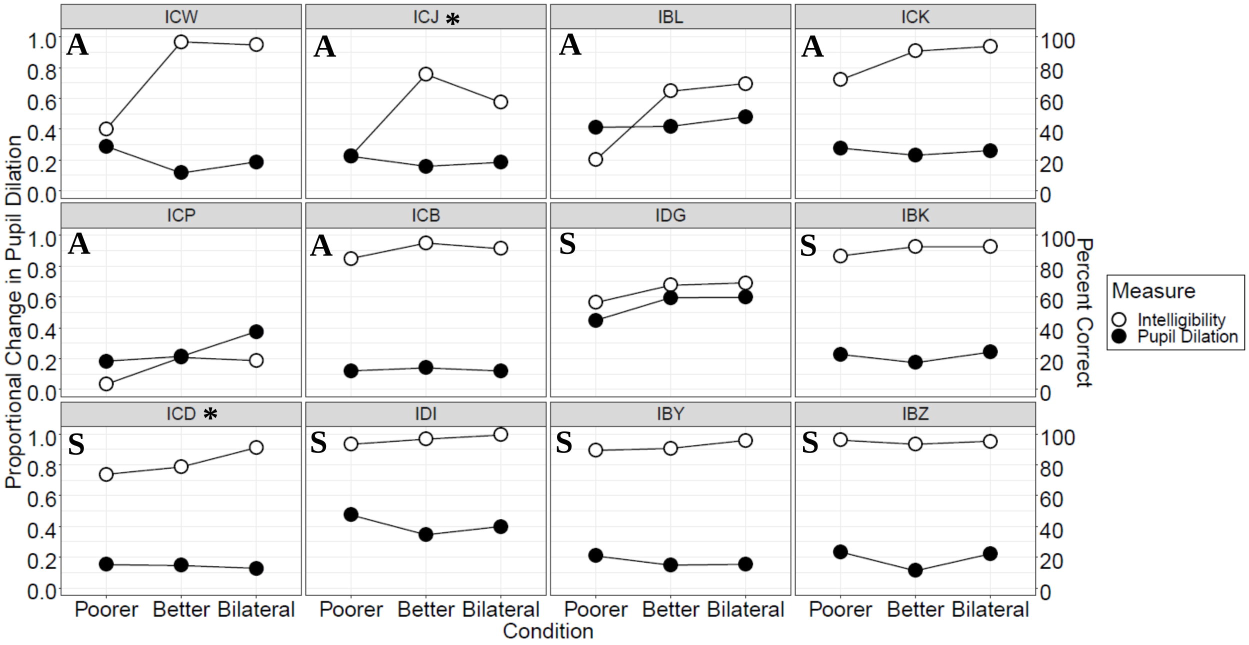


Figure 4. Speech intelligibility and maximum proportional change in pupil dilation for each participant. "A" indicates listeners who were classified as having significant interaural asymmetries (asymmetric), and "S" indicates listeners who were classified as symmetric. *ICJ exhibited a significant decrease in speech intelligibility (interference) from the Better Ear to Bilateral condition ($p<0.01$). ICD exhibited a significant increase in speech intelligibility (binaural redundancy) from the Better Ear to Bilateral condition ($p<0.01$).

VIII. References

Alhanbali, S., Dawes, P., Lloyd, S., & Munro, K. J. (2017). Self-Reported Listening-Related Effort and Fatigue in Hearing-Impaired Adults. *Ear and Hearing*, *38*(1), e39–e48. https://doi.org/10.1097/AUD.0000000000000361

Avan, P., Giraudet, F., & Büki, B. (2015). Importance of binaural hearing. *Audiology and Neurotology*. https://doi.org/10.1159/000380741

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*. https://doi.org/10.1037/0033-2909.91.2.276

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bernstein, J. G. W., Goupell, M. J., Schuchman, G. I., Rivera, A. L., & Brungart, D. S. (2016). Having two ears facilitates the perceptual separation of concurrent talkers for bilateral and single-sided deaf cochlear implantees. *Ear and Hearing*, *37*(3), 289–302. https://doi.org/10.1097/AUD.0000000000000284

Burg, E. A., Thakkar, T., Fields, T., Misurelli, S. M., Kuchinsky, S. E., Roche, J., … Litovsky, R. Y. (2021). Systematic Comparison of Trial Exclusion Criteria for Pupillometry Data Analysis in Individuals With Single-Sided Deafness and Normal Hearing. *Trends in Hearing*. https://doi.org/10.1177/23312165211013256

Friesen, L. M., & Picton, T. W. (2010). A method for removing cochlear implant artifact. *Hearing Research*, *259*(1–2), 95–106. https://doi.org/10.1016/j.heares.2009.10.012

Gagné, J. P., Besser, J., & Lemke, U. (2017). Behavioral assessment of listening effort using a dual-task paradigm: A review. *Trends in Hearing*. https://doi.org/10.1177/2331216516687287

Gantz, B. J., Tyler, R. S., Rubinstein, J. T., Wolaver, A., Lowder, M., Abbas, P., … Preece, J. P. (2002). Binaural cochlear implants placed during the same operation. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200203000-00012

Gatehouse, S., & Noble, W. G. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *International Journal of Audiology*, *43*(2), 85–99. https://doi.org/10.1080/14992020400050014

Gilley, P. M., Sharma, A., Dorman, M. F., Finley, C. C., Panch, A. S., & Martin, K. (2006). Minimization of cochlear implant stimulus artifact in cortical auditory evoked potentials. *Clinical Neurophysiology*, *117*(8), 1772–1782. https://doi.org/10.1016/j.clinph.2006.04.018

Goupell, M. J., Stakhovskaya, O. A., & Bernstein, J. G. W. (2018). Contralateral Interference Caused by Binaurally Presented Competing Speech in Adult Bilateral Cochlear-Implant Users. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000470

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Labadie, R. F., & Haynes, D. S. (2007). Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31806dc21a

Hughes, K. C., & Galvin, K. L. (2013). Measuring listening effort expended by adolescents and young adults with unilateral or bilateral cochlear implants or normal hearing. *Cochlear Implants International*. https://doi.org/10.1179/1754762812Y.0000000009

Hughes, S. E., Hutchings, H. A., Rapport, F. L., McMahon, C. M., & Boisvert, I. (2018). Social connectedness and perceived listening effort in adult cochlear implant users: A grounded theory to establish content validity for a new patient-reported outcome measure. *Ear and Hearing*, *39*(5), 922–934. https://doi.org/10.1097/AUD.0000000000000553

IEEE Recommended Practice for Speech Quality Measurements. (1969). *IEEE Transactions on Audio and Electroacoustics*, *17*(3), 225–246. https://doi.org/10.1109/TAU.1969.1162058

Kramer, S. E. (2008). Hearing impairment, work, and vocational enablement. *International Journal of Audiology*. https://doi.org/10.1080/14992020802310887

Kramer, S. E., Kapteyn, T. S., & Houtgast, T. (2006). Occupational performance: Comparing normally-hearing and hearing-impaired employees using the Amsterdam Checklist for Hearing and Work. *International Journal of Audiology*, *45*(9), 503–512. https://doi.org/10.1080/14992020600754583

Laszig, R., Aschendorff, A., Stecker, M., Müller-Deile, J., Maune, S., Dillier, N., … Doering, W. (2004). Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-Month postoperative results. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200411000-00016

Litovsky, R. Y., Parkinson, A., & Arcaroli, J. (2009). Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*, *30*(4), 419–431. https://doi.org/10.1097/AUD.0b013e3181a165be

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., & Yu, G. (2004). Bilateral Cochlear Implants in Adults and Children. *Archives of Otolaryngology - Head and Neck Surgery*, *130*(5), 648–655. https://doi.org/10.1001/archotol.130.5.648

Litovsky, R. Y., Parkinson, A., Arcaroli, J., & Sammeth, C. (2006). Simultaneous Bilateral Cochlear Implantation in Adults: A multicenter clinical study. *Ear and Hearing*, *27*(6), 714–731. https://doi.org/10.1097/01.aud.0000246816.50820.42.Simultaneous

Loizou, P. C., Hu, Y., Litovsky, R. Y., Yu, G., Peters, R., Lake, J., & Roland, P. (2009). Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3036175

Mosnier, I., Sterkers, O., Bebear, J. P., Godey, B., Robier, A., Deguine, O., … Ferrary, E. (2009). Speech performance and sound localization in a complex noisy environment in bilaterally implanted adult patients. *Audiology and Neurotology*, *14*(2), 106–114. https://doi.org/10.1159/000159121

Nachtegaal, J., Kuik, D. J., Anema, J. R., Goverts, S. T., Festen, J. M., & Kramer, S. E. (2009). Hearing status, need for recovery after work, and psychosocial work characteristics: Results from an internet-based national survey on hearing. *International Journal of Audiology*. https://doi.org/10.1080/14992020902962421

Noble, W., Tyler, R., Dunn, C., & Bhullar, N. (2008). Unilateral and bilateral cochlear implants and the implant-plus-hearing-aid profile: Comparing self-assessed and measured abilities. *International Journal of Audiology*. https://doi.org/10.1080/14992020802070770

Nopp, P., Schleich, P., & D'Haese, P. (2004). Sound localization in bilateral users of MED-EL COMBI 40/40+ cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000130793.20444.50

Ohlenforst, B., Zekveld, A. A., Lunner, T., Wendt, D., Naylor, G., Wang, Y., … Kramer, S. E. (2017). Impact of stimulus-related factors and hearing impairment on listening effort as indicated by pupil dilation. *Hearing Research*, *351*, 68–79. https://doi.org/10.1016/j.heares.2017.05.012

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., … Wingfield, A. (2016). Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL). *Ear and Hearing*, *37*, 5S-27S. https://doi.org/10.1097/AUD.0000000000000312

Privitera, C. M., Renninger, L. W., Carney, T., Klein, S., & Aguilar, M. (2010). Pupil dilation during visual target detection. *Journal of Vision*, *10*(10). https://doi.org/10.1167/10.10.3

Schleich, P., Nopp, P., & D'Haese, P. (2004). Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000130792.43315.97

Tyler, R. S., Dunn, C. C., Witt, S. A., & Noble, W. G. (2007). Speech perception and localization with adults with bilateral sequential cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31803153e2

van Hoesel, R., Ramsden, R., & O'Driscoll, M. (2002). Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. *Ear and Hearing*. https://doi.org/10.1097/00003446-200204000-00006

van Hoesel, R., & Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1539520

Wagner, A. E., Nagels, L., Toffanin, P., Opie, J. M., & Başkent, D. (2019). Individual Variations in Effort: Assessing Pupillometry for the Hearing Impaired. *Trends in Hearing*, *23*. https://doi.org/10.1177/2331216519845596

Wendt, D., Koelewijn, T., Książek, P., Kramer, S. E., & Lunner, T. (2018). Toward a more comprehensive understanding of the impact of masker type and signal-to-noise ratio on the pupillary response while performing a speech-in-noise test. *Hearing Research*. https://doi.org/10.1016/j.heares.2018.05.006

Winn, M. B., Edwards, J. R., & Litovsky, R. Y. (2015). The impact of auditory spectral resolution on listening effort revealed by pupil dilation. *Ear and Hearing*, *36*(4), e153–e165. https://doi.org/10.1097/AUD.0000000000000145

Winn, M. B., Wendt, D., Koelewijn, T., & Kuchinsky, S. E. (2018). Best Practices and Advice for Using Pupillometry to Measure Listening Effort: An Introduction for Those Who Want to Get Started. *Trends in Hearing*, Vol. 22. https://doi.org/10.1177/2331216518800869

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2010). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. *Ear and Hearing*, *31*(4), 480–490. https://doi.org/10.1097/AUD.0b013e3181d4f251

CHAPTER IV. The Effect of Simulated Asymmetric Temporal Resolution on Binaural Unmasking in Normal Hearing Adults Listening to Vocoded Speech

I. Abstract

Cochlear implants (CI) are designed to provide access to speech information in patients with severe-to-profound sensorineural hearing loss who do not benefit from hearing aids. Many CI listeners receive bilateral CIs (BiCI), and although they are able to achieve excellent speech intelligibility in quiet, there is substantial variability in binaural benefits amongst listeners, specifically, in binaural unmasking, which requires listeners to integrate signals across ears to improve performance. Further, listeners with BiCIs can experience large performance asymmetries between ears. Numerous peripheral and central factors likely contribute to the heterogeneity of binaural performance in this population. One aspect that is known to be important for speech intelligibility in CI users is temporal envelope encoding. This work aimed to investigate whether interaural differences in temporal envelope encoding (i.e., temporal resolution) contribute to asymmetric speech performance and negatively impact binaural unmasking in BiCI users. We simulated poor temporal envelope encoding in normal hearing (NH) individuals by reducing the dynamic range of vocoded speech, which has limited spectral information similar to a CI. Target stimuli consisted of female-talker IEEE sentences and masker stimuli consisted of female-talker AzBio sentences. Stimuli were processed with a 16-channel noise vocoder and presented over headphones at 65 dB-A. We investigated the effect of reduced dynamic range on speech intelligibility in quiet, and examined how symmetric and asymmetric reductions in dynamic range affected listeners’ ability to integrate signals across ears and obtain binaural unmasking. We found that speech intelligibility declined with decreasing dynamic range in both quiet and masker conditions. Additionally, binaural unmasking declined with decreasing dynamic range, and binaural unmasking was greater for symmetric compared to asymmetric conditions. These results are in line with previous findings that report temporal envelope

encoding as a relevant factor for speech intelligibility in CI listeners, and suggest that both poor and asymmetric temporal envelope encoding may contribute to the limited binaural unmasking benefit demonstrated by many BiCI users.

II. Introduction

Binaural hearing refers to the comparison and integration of auditory information across ears, and facilitates the localization of sounds and communication in noisy environments (Litovsky & Goupell, 2021). Three main benefits contribute to speech understanding in noise: the better ear effect, binaural unmasking, and binaural redundancy (Litovsky, Goupell, Misurelli, & Kan, 2017). The better ear effect refers to the ability to attend to the ear with the better signal-to-noise ratio when a signal of interest is spatially separated from masking sounds. The difference in SNR across ears is due to the head, which acts as a physical barrier, reducing the level of the of the masker at the ear farthest from the interfering source (Bronkhorst & Plomp, 1988; Culling & Lavandier, 2021; Zurek, 1993). This benefit is monaural in nature, and does not require binaural processing. Binaural unmasking arises from the auditory system's ability to utilize binaural cues (i.e., ITDs and ILDs) to group and perceptually separate target and interfering sounds that originate from different spatial locations (for review, see Avan, Giraudet, & Büki, 2015). Binaural redundancy refers to the advantage that results from having two copies of the signal, one in each ear (Avan et al., 2015). Both binaural unmasking and binaural redundancy require binaural processing (Hawley, Litovsky, & Colburn, 1999; Hawley, Litovsky, & Culling, 2004).

Individuals with normal hearing (NH) naturally have access to the benefits of binaural hearing, and individuals with hearing loss can re-gain access to these benefits using assistive devices (for review, see Ricketts & Kan, 2021). The present study focuses on patients with severe-to-profound hearing loss who receive minimal benefit from hearing aids and qualify for implantable auditory prostheses known as cochlear implants (CIs). CIs bypass the outer ear, middle ear, and cochlea, and directly stimulate the auditory nerve with electrical current (Loizou, 1999). Modern CIs have been successful in enabling many patients to achieve good speech understanding (>80%) in quiet (Firszt et al., 2004; B. S. Wilson & Dorman, 2007). Due to the known benefits of binaural hearing for sound localization and speech understanding in noise, bilateral CIs (BiCIs) have become increasingly common in an attempt to improve performance and spatial hearing abilities in these patients (e.g., Litovsky, Parkinson, Arcaroli, & Sammeth, 2006; Peters, Wyss, & Manrique, 2010). Compared to hearing aids or a unilateral CI, many patients with BiCIs demonstrate improved speech understanding in noise (e.g., Gantz et al., 2002; Litovsky et al., 2004; Loizou et al., 2009; Schleich, Nopp, & D'Haese, 2004; Tyler, Dunn, Witt, & Noble, 2007; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel & Tyler, 2003).

The literature suggests that most of the observed bilateral CI benefit is due to better-ear listening, with minimal benefit attributable to binaural unmasking (e.g., Gantz et al., 2002; Goupell, Kan, & Litovsky, 2016; Goupell, Stakhovskaya, & Bernstein, 2018; Litovsky et al., 2006; Loizou et al., 2009; Schleich et al., 2004; van Hoesel et al., 2002; van Hoesel & Tyler, 2003; Vermeire & Van De Heyning, 2009). For example, initial studies on the better ear benefit in BiCI users found that listeners can achieve ~5 dB of improvement depending on the type and configuration of the maskers (Litovsky et al., 2006; Loizou et al., 2009; Schleich et al., 2004; van Hoesel & Tyler, 2003), while binaural unmasking is weak or absent (Gantz et al., 2002; Goupell et al., 2016; Loizou et al., 2009; Schleich et al., 2004; van Hoesel et al., 2008). Other studies have shown that some BiCI users can successfully integrate information across ears to achieve a binaural unmasking benefit when target and maskers are both speech stimuli. Bernstein and colleagues (2016) tested binaural unmasking in nine adult BiCI users with relatively short inter-implant delays (mean=2.5 years between implants) and found, that while listeners were overall able to achieve a significant amount of unmasking (~5 dB), there was substantial variability across listeners. In that study, participants represented a unique group, in that eight of the nine listeners were post-lingually deafened (Bernstein et al., 2016). A follow-up study by Goupell et al. (2018) recruited nine adult BiCI listeners who were deafened early in life or had asymmetric hearing histories (i.e., one ear with a much longer duration of deafness than the other ear). Rather than demonstrate binaural unmasking, BiCI users in this study exhibited interference in the dichotic compared to the monaural condition, meaning that performance decreased when listening with two ears versus one. Further, the amount of interference was negatively correlated with speech intelligibility of the target ear, and positively correlated with duration of deafness of the target ear and speech intelligibility of the contralateral ear (Goupell et al., 2018).

To better understand the factors limiting binaural unmasking of speech in BiCI users, it is important to consider the underlying cues that facilitate this benefit. The binaural masking level difference (BMLD) is one example of binaural unmasking that utilizes an interaural phase difference between the signal and noise, to facilitate improved detection of the signal. Detection thresholds are measured when the signal and noise are identical across ears (N0S0), and compared to when the phase of the signal or noise is inverted in one ear (akin to separation of 180º, i.e., N0Sπ). Because there is no change in the signal-to-noise ratio, the improved detection is attributed to interaural difference sensitivity in the right and left ear signals (e.g., Culling & Lavandier, 2021; Lu, Litovsky, & Zeng, 2010; van Hoesel et al., 2008). When the signal is a low frequency pure tone and the noise is narrow-band, NH listeners can obtain substantial BMLDs of ~20 dB (van de Par & Kohlrausch, 1997). In similar conditions using individual pairs of pitch-matched electrodes, BiCI users demonstrate BMLDs on the order of 4.6-9 dB (Long, Carlyon, Litovsky, & Downs, 2006; Lu et al., 2010), suggesting that BiCI listeners are sensitive to changes in interaural envelope correlation. Lu et al. (2010) tested BiCI listeners and NH listeners with CI simulations, and found BMLDs for BiCI listeners of 4.6 dB and BMLDs for NH listeners of 14.4 dB with noise-vocoded stimuli, and 12.6 dB for Gaussian-envelope tone vocoded stimuli. The presence of BMLDs in the vocoder conditions indicate that envelope cues were sufficient to convey binaural phase difference information in this study. Thus, the lack of temporal fine structure conveyed to CI users cannot explain the performance gap between BiCI and NH listeners with CI simulations (Lu et al., 2010). The authors proposed that the disparity in performance was due to differences in central processing of binaural information, rather than a limitation in peripheral encoding. This conclusion was supported by the finding that the two subjects with the largest BMLDs (~9.75 dB) also had the longest duration of bilateral CI experience, and two subjects with very small BMLDs either had shorter bilateral experience or early onset of deafness. However, another subject who had a late onset of deafness and only one less year of bilateral experience than the best performers demonstrated an average BMLD of only 1.2 dB. While the small BMLDs in these listeners may be due in part to central processing difficulties, additional insight may be gained by examining the difference in speech performance across ears. For the two listeners with the smallest BMLDs, one had extremely poor speech perception in both ears (0% in quiet), and another had substantial asymmetry in speech perception (difference of 68% between the left and right ear in quiet), suggesting that peripheral factors cannot be ruled out.

While it is promising that some studies have shown BMLDs in BiCI listeners, the ecological validity of these experiments may have some limitations, due to the fact that the stimuli were delivered to single pitch-matched electrode pairs using temporally synchronized research interfaces. Additionally, a 180º phase inversion of a 125 Hz tone is equivalent to an ITD of 4ms, which is far beyond what is possible in real life based on the average width of an adult head (i.e., ~800µs) (Culling & Lavandier, 2021). van Hoesel et al. (2008) examined binaural unmasking of speech in four BiCI listeners using a similar BMLD paradigm in which speech sentences were presented in spectrally matched noise using direct audio input to the processors. They compared conditions in which the speech and noise were presented monaurally (SmNm) and the noise was presented diotically (SmN0), to conditions in which the speech and noise were both presented diotically (S0N0) and the speech was presented with an ecologically valid ITD of 700µs (S700N0). They failed to find significant unmasking for any of the conditions tested. This is not surprising considering the fact that they used speech stimuli, which have been shown to elicit smaller BMLDs than tones. For example, NH listeners can obtain BMLDs of up to ~20 dB with tonal stimuli, but exhibit BMLDs on the order of ~7 dB for speech stimuli (e.g., Johansson & Arlinger, 2002; R. H. Wilson, Hopkins, Mance, & Novak, 1982; Zirn, Arndt, Aschendorff, Laszig, & Wesarg, 2016). Additionally, van Hoesel et al. (2008) utilized noise as the masker, and a subsequent study by Bernstein and colleagues showed that a noise masker was not sufficient to elicit binaural unmasking in BiCI users, but a speech masker was (Bernstein et al., 2016).

Several factors likely contribute the small or absent binaural unmasking benefit seen in BiCI users. First, processors do not preserve the temporal fine structure of auditory stimuli, leaving CI listeners to rely on temporal envelope information for speech understanding and auditory source segregation (Loizou, 1999). Evidence from studies in NH listeners suggests that access to temporal fine structure information provides added benefits compared to when only envelope information is available (Lu et al., 2010; van de Par & Kohlrausch, 1997). In BiCI users, even when envelope cues are available, the encoding of this information can be degraded due to factors like poor neural health and electrical current spread (Long et al., 2014). Further, when these factors differ across ears, BiCI listeners are faced with the challenge of integrating asymmetric inputs. Asymmetries in the peripheral encoding of temporal envelope information combined with the processors working independently (i.e., lack of synchronized stimulation) may result in reduced interaural correlation (IC) for diotic stimuli, making it more difficult to perceive changes to IC in dichotic conditions, leading to reduced BMLDs (Goupell & Litovsky, 2015). Similarly, in speech binaural unmasking studies, BiCI users with large asymmetries may not be able to adequately fuse diotic noise or speech masker stimuli across ears to perceive a perceptual separation of the target and maskers (Aronoff, Shayman, Prasad, Suneel, & Stelmach, 2015). The importance of IC in binaural fusion is supported by studies showing that NH listeners perceive perfectly correlated stimuli as a single unified sound, and stimuli with reduced IC as being wider or more diffuse. At very low ICs, listeners may perceive multiple sounds (Sayers & Cherry, 1957; Wess, Spencer, & Bernstein, 2020; Whitmer, Seeber, & Akeroyd, 2012). Thus, inadequate fusion or lack of fusion would result in the perception of a large and diffuse masker, or even two separate maskers, one in each ear, precluding unmasking of the target signal.

In the present study we aimed to investigate the impact of poor temporal encoding on speech intelligibility in quiet and with speech maskers, as well as the effect of asymmetric temporal encoding on binaural unmasking of speech. Because it is difficult to control for temporal degradation in BiCI listeners, this study used CI simulations (vocoders) in NH listeners. One approach for degrading temporal envelope information is to compress the dynamic range (DR) of the speech stimulus, effectively reducing amplitude modulations (AM) in the speech envelope (Fu, 2002). Our experimental set-up replicates the paradigm used by previous studies investigating binaural unmasking in BiCI, single-sided deafness CI (SSD-CI), and NH listeners using vocoded speech (Bernstein et al., 2016; Bernstein, Stakhovskaya, Jensen, & Goupell, 2020; Goupell et al., 2016, 2018). When this paradigm is implemented using headphones, baseline speech intelligibility with target and masker speech presented to one ear (monaural) is compared to a dichotic condition in which the target is presented to one ear and the masker is presented concurrently to both ears. Listeners who are able to fuse masker stimuli presented to the two ears can perceive separation of the target and masker speech. That is, the target speech is perceived towards the side of the head and the masker is perceived near the center of the head, resulting in increased intelligibility of the target talker (Bernstein et al., 2016). This is similar to spatial release from masking in the free field, except that it eliminates the possibility for listeners to use monaural benefits like head shadow, and instead requires listeners rely solely on binaural interactions for improved speech intelligibility. Testing NH listeners with vocoded speech allows us to simulate aspects of CI processing while limiting the amount of inter-subject variability and controlling performance level and degree of interaural asymmetry. We hypothesized that speech intelligibility in quiet and masker conditions would decline with decreasing DR. Additionally, we hypothesized that binaural unmasking would decrease with decreasing DR, and that asymmetric reductions in DR would negatively affect binaural unmasking more than symmetric reductions across ears.

III. Experiment I: Effect of Asymmetric Dynamic Range on Binaural Unmasking of Vocoded Speech

A. Methods

a. Participants

Nine NH native English-speaking young adults (age range 19-31 years) were recruited from the University of Wisconsin-Madison and the surrounding community to participate in the experiment. All participants were required to pass a hearing screening at 20 dB HL at octave frequencies from 250-8000 Hertz in order to be eligible for the study.

b. Stimuli

Target stimuli consisted of open-set sentences drawn from the Institute of Electrical and Electronics Engineers sentence corpus and were spoken by a female ("IEEE Recommended Practice for Speech Quality Measurements," 1969). Masker stimuli consisted of open-set sentences drawn from the AzBio sentence corpus and were spoken by a different female (Spahr et al., 2012). Target sentences ranged from 4000-6000 ms in duration and contained five key words per sentence. All stimuli were processed using a 16-channel low-noise noise (LNN) vocoder to simulate CI processing. While clinical processors stimulate 8-10 channels at a given time, we aimed to degrade stimuli by reducing temporal resolution. Therefore, we used a 16-vocoder rather than an 8-channel vocoder in order to examine a wide range of temporal resolution while avoiding floor effects due to poor spectral resolution. The motivation for using LNN was that these carriers have an essentially flat temporal envelope like a sinewave, enabling a better representation of the temporal envelope in each channel compared to narrow band noise. This is important because DR was reduced by compressing the temporal envelope in each channel. To reduce the fidelity of temporal information, DR of the stimuli were compressed to 100% (no compression), 71%, 50%, 35%, and 25% of the original DR. DRs were chosen based on preliminary data to evenly sample along the psychometric function of performance. This manipulation was implemented in the signal processing of our stimuli after the envelope in each vocoder channel was extracted and before the LNN carriers were modulated by the envelope (Figure 3). Overall intensity was equalized following envelope compression so that compressed stimuli were the same intensity as non-compressed stimuli. Stimuli were calibrated to 65 dBA sound pressure level.

c. Equipment and Procedure

Testing took place in the Binaural Hearing and Speech Lab (PI: Ruth Litovsky) at UW-Madison. Stimuli were played to circumaural headphones (Sennheiser HD 600) through a Tucker-Davis Technologies System III. Testing took place in a double-walled sound attenuating booth and a computer with customized software written in MATLAB was used to create the participant user interface and deliver stimuli.

Three stimulus configurations were tested: Quiet, Monaural, and Dichotic. The target ear was randomly selected for each participant (Left: n=2, Right: n=7). For Dichotic configurations, the DR of the stimulus was reduced in one ear or in both ears, in order to create asymmetric and symmetric DR conditions, respectively (Table 1). Previous work has shown that BiCI users are more likely to demonstrate interference when the target is presented to the worse performing ear (Bernstein et al., 2020; Goupell et al., 2018); thus, for asymmetric conditions, only DR of the target ear was compressed, effectively making the target ear the “worse” ear. This ensured that we were replicating the most difficult conditions for BiCI listeners in this paradigm. Within one level of DR, the DR of the target ear was held constant to allow for comparisons between monaural, symmetric, and asymmetric conditions. For dichotic configurations, DR of the contralateral was either the same as the target ear (Symmetric) or kept at 100% DR (Asymmetric). In all dichotic conditions, the phase of the masker in the contralateral ear was inverted. This was done in order isolate the effect of envelope correlation on masker fusion by preventing fusion of symmetric maskers due to fine structure correlation of the noise carriers.

Masker sentences were concatenated into a long stream, and the starting sample of the maskers was randomly selected for each trial. Maskers began 250 ms prior to the onset of the target sentence, and ended 250 ms after the offset of the target. Monaural and Dichotic conditions were tested at an SNR of 0 dB. In the Quiet configuration, the target stimulus was presented alone to one ear. A Control condition in which the target and contralateral masker were kept at 100% DR, and the masker ipsilateral to the target was compressed to 50% DR was also included. This condition ensured that differences between symmetric and asymmetric conditions were due to differences in the ability to fuse asymmetric maskers rather than difficulty ignoring a salient masker while attending to a degraded target.

Listeners verbally repeated target sentences and responses were scored by an experimenter. 30 trials per listening condition were separated into two runs. Condition runs were separated into two blocks, and order of conditions was randomized within each block to prevent practice effects. Listeners completed a short procedure to familiarize them with the task and the target talker’s voice prior to starting experiment.

d. Statistical Analysis

The effect of DR compression on speech intelligibility in the Quiet condition was evaluated using a one-way repeated measure analysis of variance (ANOVA) with DR (five levels: 100%, 71%, 50%, 35%, 25%) as the independent variable and speech intelligibility (percent of words correctly repeated) as the dependent variable. Post-hoc pairwise comparisons were completed with paired t-tests using the Benjamini-Hochberg method to control false discovery rate (Benjamini & Hochberg, 1995). Second, we examined the effect of DR compression on speech intelligibility in the monaural and dichotic configurations using a two-way repeated measures ANOVA with condition (three levels: Monaural, Symmetric, Asymmetric) and DR (three levels: 71%, 50%, 35%) as the independent variables and speech intelligibility as the dependent variable. In order to look at the main effects of DR and condition on speech intelligibility, the 100% DR conditions were excluded from this omnibus test because they did not have an asymmetric counterpart. Additionally, the monaural and dichotic Control conditions were also excluded. Post-hoc pairwise comparisons were completed with paired t-tests using the Benjamini-Hochberg method to control false discovery rate. Assumptions for omnibus and post-hoc tests were statistically evaluated using the Shapiro-Wilk normality test and Mauchly’s Test of Sphericity. An alpha of 0.05 was used to determine whether results were significantly different from chance.

B. Results

Mean speech intelligibility as a function of DR for the Quiet condition is shown in Figure 2. One participant did not complete the 25% DR condition and was excluded from the quiet analysis, resulting in n=8 for this configuration only. Speech intelligibility declined with decreasing DR in Quiet, with the 100% DR condition eliciting an average of 96.9% correct, and the 25% DR condition eliciting an average of 17.1% correct, indicating that the DRs chosen elicited a wide range of performance. A one-way repeated measures ANOVA revealed a significant main effect of DR on percent correct score [$F(4,28)=237.8$, $p<0.0001$]. Post-hoc pairwise comparisons were completed for adjacent levels of DR and revealed that percent correct decreased significantly for each reduction in DR (Figure 3; $p<0.001$ for 71-50%, 50-35%, 35-25% and $p<0.05$ for 100-71%). These results are in line with previous findings demonstrating the negative effect of reduced DR on speech intelligibility in NH individuals listening to vocoded speech (Loizou, Dorman, & Fitzke, 2000).

Similar to the Quiet condition, speech intelligibility declined with decreasing DR for all three masker conditions (Figure 3). Compared to the Quiet 100% DR condition in which participants scored an average of 96.9% correct, performance declined substantially with the introduction of a same-sex speech masker in the ipsilateral ear (monaural condition), resulting in an average of 50.3% correct. Similarly, participants scored an average of 44.3% correct in the Quiet 35% DR condition, but dropped to floor level performance in the Monaural 35% DR condition (mean = 2.8% correct). In general, the Symmetric condition elicited the best performance, followed by the Asymmetric condition, and finally the Monaural condition. A two-way repeated measures ANOVA revealed significant main effects of condition [$F(2,16)=89.1$, $p<0.0001$] and DR [$F(2,16)=558.3$, $p<0.0001$] on speech intelligibility, as well as a significant interaction between condition and DR [$F(4,32)=28.8$, $p<0.0001$]. Therefore, the effect of condition will be examined separately for each level of DR.

Binaural unmasking for Symmetric and Asymmetric conditions at all levels of DR are plotted in Figure 4. Binaural unmasking was calculated as the difference in speech intelligibility between the Monaural and Symmetric or Asymmetric dichotic conditions (e.g., Symmetric %Correct-Monaural %Correct=Binaural Unmasking). Post-hoc pairwise comparisons between the Monaural and Symmetric, and the Monaural and Asymmetric conditions within each level of DR were completed in order to evaluate whether performance in Symmetric and Asymmetric conditions was significantly different from the Monaural condition (indicating binaural unmasking). Additionally, pairwise comparisons between Symmetric and Asymmetric conditions within each level of DR were completed in order to evaluate whether these conditions elicited different amounts of unmasking. Results revealed that adding a copy of the masker to the contralateral ear with the same DR as the ipsilateral masker (symmetric conditions) elicited a significant amount of binaural unmasking for all levels of DR (p<0.01 for all levels of DR). In contrast, adding a copy of the masker to the contralateral ear with 100% DR (Asymmetric conditions) only elicited significant binaural unmasking at the 71% DR level. Further, the difference in unmasking between Symmetric and Asymmetric conditions was significant at all levels of DR, with the Symmetric conditions eliciting greater unmasking than the Asymmetric conditions (Figure 4; p<0.01 for all levels of DR).

Our omnibus test revealed a significant interaction between DR and condition. As mentioned previously, speech intelligibility declined with decreasing DR of the target ear, however, decreasing DR of the target ear had a larger negative effect on performance in the Symmetric and Asymmetric conditions than the Monaural condition (evidenced in Figure 3 by the convergence of data points as DR of the target ear decreases). This effect is also shown in Figure 4 by the reduction in binaural unmasking (the difference between monaural and dichotic conditions) as DR of the target ear decreases. In fact, some participants experienced interference rather than unmasking in the Asymmetric 50% DR (shown by the error bar that extends below 0). This is also seen for the Asymmetric 35% DR condition, in which the mean difference between the Monaural and Asymmetric condition was negative (-0.7%).

The Control condition was included in order to investigate whether differences in unmasking between symmetric and asymmetric conditions were due to difficulty attending to degraded speech while simultaneously ignoring a more intelligible speech masker. In order to evaluate this possibility, binaural unmasking in the Symmetric 100% DR condition was compared to binaural unmasking in the Control condition. The only difference between these conditions was the DR of the masker ipsilateral to the target, which was kept at 100% in the Symmetric 100% DR condition, and reduced to 50% DR in the Control condition. By keeping the target talker and contralateral masker at 100% DR in both conditions, we could ensure that any differences in unmasking were due to a lack of perceptual separation between target and masker due to the asymmetric maskers in the Control condition. Results from a paired t-test comparing binaural unmasking for both conditions revealed that the Symmetric 100% DR condition elicited significantly more unmasking than the Control condition ($p<0.01$).

IV. Interim Discussion

Speech intelligibility in quiet and speech masker conditions was measured in NH individuals presented with vocoded speech stimuli over headphones. The dynamic range of the stimuli was reduced symmetrically or asymmetrically across ears in order to simulate degraded and asymmetric envelope encoding in BiCI users at various levels of performance. Binaural unmasking, a speech-in-noise benefit that results from the successful integration of binaural information, was assessed by measuring the difference in speech intelligibility in Monaural and Dichotic conditions. At the 100% and 71% DR levels, listeners demonstrated high speech intelligibility in the Quiet condition, and significant unmasking for the symmetric condition (33.2% and 41.2% respectively). This is similar to Bernstein and colleagues (2016), who observed ~38% of binaural unmasking for NH individuals using the same headphone paradigm and different vocoded speech stimuli (it should be noted that percent correct scores were transformed to rationalized arcsine units in the Bernstein study).

The primary goal of the Experiment I was to examine the effect of asymmetric DR on binaural unmasking. We observed significantly less unmasking with asymmetric maskers compared to symmetric maskers for every DR level tested. In fact, the only DR level in which the asymmetric condition elicited significant unmasking was 71% DR. As DR of the target ear was further reduced to 50% and 35%, unmasking decreased substantially, and some NH listeners demonstrated interference, a decrement in performance compared to the monaural condition when a copy of the masker was added to the contralateral ear. This interference effect has been the topic of recent papers investigating binaural unmasking in BiCI and SSD-CI users. In these studies, SSD-CI users demonstrated unmasking when the target was presented to the acoustic (better) ear, and interference when the target was presented to the CI ear (Bernstein et al., 2016, 2020). SSD-CI users are similar to asymmetric BiCI users in some respects due to the disparity in signal fidelity between acoustic and electric hearing. Similarly, BiCI users who were post-lingually deafened and had relatively short inter-implant delays demonstrated unmasking when the target was presented to the better ear, and BiCI users with early onset of deafness or asymmetric hearing histories demonstrated interference for both the better and poorer ear (Bernstein et al., 2016; Goupell et al., 2018). Further, for asymmetric BiCI users, the amount of interference was inversely related to speech intelligibility of the target ear, and directly correlated with and duration of deafness of the target ear and speech intelligibility of the contralateral ear (Goupell et al., 2018). Similar trends were observed in the present study. Symmetric conditions elicited binaural unmasking for all levels of DR, which may be similar to presenting the target to the “better ear” of a symmetric BiCI listener. In contrast, for asymmetric conditions in which the target was presented to the “worse” ear, listeners demonstrated significantly less unmasking than corresponding symmetric conditions, and were more likely to demonstrate interference as degree of asymmetry increased. To our knowledge, this is the first study that has replicated this interference effect in NH listeners using vocoded stimuli, which indicates that this effect may be related to poor and/or asymmetric peripheral encoding in CI users. The ability to elicit interference in NH listeners could be very useful for identifying different factors that might contribute to this effect in CI users. Finally, for both symmetric and asymmetric conditions, binaural unmasking decreased as DR of the target ear decreased. This suggests that the poorer ear limits binaural unmasking even in the absence of interaural asymmetry.

We note a limitation of Experiment I regarding the comparison of symmetric and asymmetric conditions in the processing of our stimuli. Target and masker stimuli were batch processed with the vocoder one time for each level of DR. Each time the stimuli are processed, the vocoder generates random noise tokens that correspond to the frequency range of each vocoder channel. Since we only processed our stimuli once for each level of DR, stimuli for the symmetric conditions had identical noise carriers across ears, while stimuli for the asymmetric conditions had independently generated noise carriers for each ear (e.g., stimuli for 100% DR and 71% DR levels were batch processed separately). Prior to playing stimuli to the headphones, the phase of the contralateral masker was inverted 180º. Without this phase inversion, noise carriers for symmetric stimuli would have had perfect interaural correlation (IC=1), resulting in a degree of fusion that would extend beyond that for just correlated envelopes. Inverting the phase of either the target or masker stimuli across ears in BMLD studies facilitates binaural unmasking, however, since we only presented the target to one ear, it is unlikely that this phase inversion contributed to unmasking in the present study. In fact, when the phase of a low frequency pure tone is inverted 180º, the result is the perception of the tone being pulled from the center of the head to each ear, facilitating unmasking from the diotic noise which is perceived centrally. This unmasking effect results from sensitivity to the phase difference of low frequency information across ears. The BMLD effect is significantly smaller with speech stimuli because intelligibility relies heavily on higher frequency information, for which we are not sensitive to phase differences (ANSI S3.5, 1997; Culling & Lavandier, 2021; Levitt & Rabiner, 1967). Thus, if the phase inversion did pull the symmetric maskers to either ear, the effect was small compared to what would occur for low frequency stimuli, and it is unlikely that it would facilitate unmasking in the present study because the target was presented monaurally, not diotically. The asymmetric maskers, on the other hand, had uncorrelated noise carriers (IC=0), so a phase inversion should not have caused any significant change in percept for these conditions.

The underlying assumption for the paradigm used in this study is that the addition of a contralateral masker facilitates a perceptual separate of target and masker speech compared to the monaural condition by pulling the masker to the center of the head while the target is perceived off to the side (in the ear it is presented to) (Bernstein et al., 2016). If the phase inversion did reduce fusion of the symmetric maskers, the observed unmasking difference between symmetric and asymmetric conditions may have been minimized (i.e., it would be larger if the noise carriers for the symmetric condition were uncorrelated, like those for the asymmetric condition). In order to investigate this possibility, we conducted a second experiment in which we processed the stimuli with all levels of DR a second time, and included an additional condition in which the noise carriers for symmetric stimuli were uncorrelated across ears.

V. Experiment II: Effect of Noise Carrier Correlation on Binaural Unmasking of Vocoded Speech

A. *Methods*

All methods were identical to those for Experiment I unless specifically stated.

a. Participants

Eleven NH native English-speaking young adults (age range 18-23 years) were recruited from the University of Wisconsin-Madison and the surrounding community to participate in Experiment II. These participants were different from those who participated in Experiment I. All participants were required to pass a hearing screening at 20 dB HL at octave frequencies from 250-8000 Hertz in order to be eligible for the study.

b. Stimuli

A second version of the stimuli were created for each level of DR. The result was two versions of the stimuli that were matched temporally and spectrally, but had independently generated noise carriers.

c. Equipment and Procedure

In addition to conditions tested in Experiment I, a third dichotic condition was also included: Symmetric DR with uncorrelated noise carriers (Table 2). This differed from the Symmetric condition tested in Experiment I which presented the exact same version of the masker, 180° out of phase across ears (IC=-1). For the new uncorrelated Symmetric condition, two independently generated versions of the maskers were presented to either ear (Table 2). This resulted in an IC of 0. For clarity, the original anti-correlated Symmetric DR condition will be referred to as “Symmetric Anti-Corr,” and the new uncorrelated Symmetric DR condition will be referred to as “Symmetric No Corr.”

d. Statistical Analysis

The effect of DR compression on speech intelligibility in the Quiet condition was evaluated using a one-way repeated measure analysis of variance (ANOVA) with DR (five levels: 100%, 71%, 50%, 35%, 25%) as the independent variable and speech intelligibility (percent of words correctly repeated) as the dependent variable. Post-hoc pairwise comparisons were completed with paired t-tests using the Benjamini-Hochberg method to control false discovery rate (Benjamini & Hochberg, 1995). Second, we examined the effect of DR compression on speech intelligibility in the monaural and dichotic configurations using a two-way repeated measures ANOVA with condition (four levels: Monaural, Symmetric No Corr, Symmetric Anti-Corr, Asymmetric) and DR (three levels: 71%, 50%, 35%) as the independent variables and speech intelligibility as the dependent variable. In order to look at the main effects of DR and condition on speech intelligibility, the 100% DR conditions were excluded from this omnibus test because they did not have an asymmetric counterpart. Additionally, the monaural and dichotic Control conditions were also excluded. Post-hoc pairwise comparisons were completed with paired t-tests using the Benjamini-Hochberg method to control false discovery rate. Assumptions for omnibus and post-hoc tests were statistically evaluated using the Shapiro-Wilk normality test and Mauchly's Test of Sphericity. An alpha of 0.05 was used to determine whether results are significantly different from chance.

B. Results

Mean speech intelligibility as a function of DR for the Quiet condition is shown in Figure 4. Speech intelligibility declined with decreasing DR in Quiet, with the 100% DR condition eliciting an average of 96.8% correct, and the 25% DR condition eliciting an average of 6.2% correct. Mauchly's Test for Sphericity returned a significant p-value (p=0.04), indicating that the data violated the assumption of sphericity. A one-way repeated measures ANOVA using a Greenhouse-Geisser correction revealed a significant main effect of DR on percent correct score [$F(4,40)=731.3$, $p<0.0001$]. Post-hoc pairwise comparisons were completed for adjacent levels of DR and revealed that percent correct decreased significantly for each reduction in DR (Figure 4; $p<0.001$ for all comparisons). These results are in line with previous findings and those reported in Experiment I (Loizou et al., 2000).

Speech intelligibility declined with decreasing DR for all four masker conditions (Figure 5). Compared to the Quiet 100% DR condition in which participants scored an average of 96.8% correct, performance declined substantially with the introduction of a same-sex speech masker in the ipsilateral ear (monaural condition), resulting in an average of 35.9% correct. Similarly, participants scored an average of 28.8% correct in the Quiet 35% DR condition, but dropped to floor level performance in the Monaural 35% DR condition (mean = 2.3% correct). Performance of the Experiment II group was worse overall than the Experiment I group. In general, the Symmetric Anti-Corr condition elicited the best performance (mean across 71%, 50%, 35% DR=31.4% correct), followed by the Symmetric No Corr condition (mean across 71%, 50%, 35% DR=23.7% correct), then Asymmetric condition (mean across 71%, 50%, 35% DR=19.7% correct), and finally the Monaural condition (mean across 71%, 50%, 35% DR=8.8% correct). In line with Experiment I, a two-way repeated measures ANOVA revealed significant main effects of condition [$F(3,30)=96.9$, $p<0.0001$] and DR [$F(2,20)=408.4$, $p<0.0001$] on speech intelligibility, as well as a significant interaction between condition and DR [$F(6,60)=23.9$, $p<0.0001$]. Therefore, the effect of condition will be examined separately for each level of DR.

Binaural unmasking for Symmetric Anti-Corr, Symmetric No Corr, and Asymmetric conditions at all levels of DR are plotted in Figure 6. Post-hoc pairwise comparisons between the

Monaural and each dichotic condition within each level of DR were completed in order to evaluate whether performance in dichotic conditions was significantly different from the Monaural condition (indicating binaural unmasking). Additionally, pairwise comparisons between dichotic conditions within each level of DR were completed in order to evaluate whether these conditions elicited different amounts of unmasking. Consistent with findings from Experiment I, adding a copy of the masker to the contralateral ear with the same DR as the ipsilateral masker and an IC of -1.0 (Symmetric Anti-Corr condition) elicited a significant amount of binaural unmasking for all levels of DR (p<0.001 for 100% through 50% DR, p<0.05 for 35% DR). In contrast, adding a copy of the masker to the contralateral ear with 100% DR and an IC of 0.0 (Asymmetric conditions) only elicited significant binaural unmasking at the 71% DR level (p<0.001). This is also consistent with results from Experiment I. On average, the Symmetric No Corr condition (IC=0.0) elicited less unmasking than the Symmetric Anti-Corr condition, and more unmasking than the Asymmetric condition. The amount of unmasking was significant at every level of DR except 35% (p<0.001 for all). The Symmetric Anti-Corr condition elicited significantly more unmasking than Symmetric No Corr and Asymmetric conditions at 71%, 50%, and 35% DR levels. Further, participants demonstrated significantly more unmasking in the Symmetric No Corr condition than the Asymmetric condition at 50% and 35% DR levels (Figure 6).

Our omnibus test revealed a significant interaction between DR and condition. Similar to Experiment I, speech intelligibility declined with decreasing DR of the target ear, and decreasing target ear DR had a larger negative effect on performance in the dichotic conditions than the Monaural condition. However, it should be noted performance of the Experiment II group was worse overall than the Experiment I group, so speech intelligibility in the Monaural condition was near floor level for both 50% and 35% DR levels (Figure 5), and therefore could not further decrease with additional decline in DR. This effect is also shown in Figure 6 by the reduction in binaural unmasking (the difference between monaural and dichotic conditions) as DR of the target ear decreases. Interestingly, several participants demonstrated interference in Experiment I in the Asymmetric 50% and 35% conditions. This interference effect was also observed in Experiment II for Asymmetric 50% and 35% conditions, and was also seen in the Symmetric No Corr 35% DR condition (Figure 6). The mean difference between the Monaural and Asymmetric condition at 35% DR was negative (-1.0).

The Control condition was also included in Experiment II in order to investigate whether differences in unmasking between Symmetric (No Corr and Anti-Corr) and Asymmetric conditions were due to difficulty attending to degraded speech while simultaneously ignoring a more intelligible speech masker. In order to evaluate this possibility, binaural unmasking in both Symmetric 100% DR conditions were compared to binaural unmasking in the Control condition. By keeping the target talker and contralateral masker at 100% DR in both conditions, we could ensure that any differences in unmasking were due to a lack of perceptual separation between target and masker due to the asymmetric maskers in the Control condition. Results from paired t-tests for both comparisons revealed that participants experienced significantly more unmasking in the Symmetric Anti-Corr 100% DR and Symmetric No Corr 100% DR conditions compared to the Control condition ($p<0.001$ for both).

VI. General Discussion

Acoustic speech carries important spectro-temporal information in both the envelope and fine structure. CI processing breaks this acoustically rich signal down into a finite number of frequency channels, discards the fine structure, and delivers envelope information to CI users via amplitude modulated high frequency pulse trains (Loizou, 1999). The result is a version of the original speech signal that is spectrally degraded. Despite the relatively crude information conveyed by the implant, many CI users are able to achieve excellent speech intelligibility in quiet situations (e.g., Firszt et al., 2004; Litovsky et al., 2006; B. S. Wilson & Dorman, 2007). It typically takes between several months and a year for CI users to adapt to this new mode of hearing (Litovsky et al., 2006), and studies have shown that patients may adjust their perceptual weighting for phonetic cues to place less emphasis on spectral information and more weight on information in the temporal domain (Winn, Chatterjee, & Idsardi, 2012). Listening and communicating in quiet environments only requires listeners to pay attention to their better ear. However, in acoustically complex environments, having access to two ears is beneficial. In these situations, NH listeners make use of binaural information to perceptually organize sounds and segregate speech from background noise. BiCI users are able to effectively utilize benefits that are available from having access to sound in both ears, but that do not rely on binaural processing (i.e., better ear effect). However, BiCI users typically do not exploit binaural benefits to the extent that NH listeners can (Gantz et al., 2002; Goupell et al., 2016; Litovsky, Parkinson, & Arcaroli, 2009; Litovsky et al., 2006; Loizou et al., 2009; Schleich et al., 2004; van Hoesel et al., 2008; van Hoesel & Tyler, 2003). BiCI users’ ability to access binaural hearing benefits may be limited by interaural asymmetries. Differences in neural health and electrical current spread, as well as the lack of synchronized stimulation across CI processors can contribute to asymmetries in the encoding of important temporal envelope information, ultimately precluding successful binaural integration and the accompanying benefits (Goupell & Litovsky, 2015; Long et al., 2014). The present study sought to examine how asymmetric temporal envelope encoding affects binaural unmasking of speech in BiCI users using simulations in NH listeners.

Experiments I and II measured speech intelligibility in quiet and speech masker conditions in NH individuals listening to vocoded speech stimuli over headphones. The dynamic range of the stimuli was reduced symmetrically or asymmetrically across ears in order to simulate degraded and asymmetric envelope encoding in BiCI users at various levels of performance. Binaural unmasking, a speech-in-noise benefit that results from the successful integration of binaural information, was assessed by measuring the difference in speech intelligibility in Monaural and Dichotic conditions. Experiment I found that speech intelligibility in Quiet declined as the DR of the speech signal was reduced. Additionally, listeners demonstrated significant unmasking for the Symmetric condition at all levels of DR. In contrast, significant unmasking for the Asymmetric condition was only observed at 71% DR. Importantly, binaural unmasking was significantly smaller for Asymmetric conditions compared to Symmetric conditions at all levels of DR, and some listeners demonstrated interference in the 50% and 35% DR conditions, suggesting that interaural asymmetry was detrimental to binaural integration. A limitation of Experiment I was that the Symmetric and Asymmetric conditions had different degrees of IC (-1 and 0, respectively). Since our paradigm assumes that listeners obtain binaural unmasking by perceptually separating the target and masker speech in dichotic compared to monaural configurations (Bernstein et al., 2016), it is possible that an IC of -1 may have limited unmasking in the Symmetric conditions by hindering fusion of the masker across ears. Experiment II sought to explore this possibility by including an additional set of Symmetric conditions that presented maskers with interaurally uncorrelated noise carriers.

Results from Experiment II corroborated those observed in Experiment I for Quiet, Monaural, Symmetric Anti-Corr, and Asymmetric conditions. Contrary to our prediction, the Symmetric No Corr condition elicited significantly less unmasking than the Symmetric Anti-Corr conditions for 71%, 50%, and 35% DR levels. This is somewhat surprising based on previous work examining the effect of IC on perceived auditory source width and studies demonstrating BMLDs with speech stimuli. As IC decreases from one to zero, a broadband sound changes from a single auditory object to a wider and more diffuse percept (Blauert & Butler, 1985; Wess et al., 2020; Whitmer et al., 2012). Further, NH listeners can obtain BMLDs for speech in noise stimuli when the speech is inverted 180º across ears and the noise is presented diotically. Therefore, we reasoned that the Symmetric Anti-Corr conditions would likely be perceived as wider or less fused than the Symmetric No Corr condition based on the anti-phasic noise carriers, which would pull the percept to either ear. While change in percept would elicit unmasking in BMLD studies, we predicted that this would negatively affect unmasking in the present study since the target was presented to only one ear rather than diotically. By comparison, the Symmetric No Corr maskers would still be perceived as diffuse due to their uncorrelated carriers, but would be more centered than the anti-phasic carriers. One possibility for the opposite effect that we observed is that the high frequency information in the speech masker dominated perception, so the phase inversion did not significantly affect masker fusion or separation of target and masker because humans are not as sensitive to changes in interaural phase of high frequencies. This possibility is supported by the comparatively smaller BMLDs observed for speech stimuli compared to low frequency stimuli (Johansson & Arlinger, 2002; R. H. Wilson et al., 1982; Zirn et al., 2016).

The principle finding in Experiment II was the difference between the Symmetric No Corr and Asymmetric conditions. The Symmetric No Corr condition facilitated significantly more binaural unmasking than the Asymmetric condition for 50% and 35% DR levels. This indicates that asymmetric temporal envelope encoding negatively affects binaural unmasking of vocoded speech. This finding is supported by studies that have investigated binaural unmasking of speech in NH individuals with SSD-CI simulations (i.e., one vocoded ear, one acoustic ear). These studies found that binaural unmasking was reduced with single-sided vocoders compared to unprocessed stimuli, and that unmasking decreased with increasing spectral or temporal mismatch across ears (Bernstein et al., 2016; Wess, Brungart, & Bernstein, 2017). Similar effects were observed when testing binaural fusion in NH individuals listening to BiCI simulations with interaural asymmetries in spectral compression; binaural fusion decreased with increasing spectral compression in one ear (Aronoff et al., 2015).

It is difficult to isolate the effect of asymmetry from the effect of the poorer ear in BiCI users since we cannot control performance in actual patients. In other words, it would be difficult to find two patients who differed solely in the amount of asymmetry observed across ears (i.e., performance of the poorer ear would have to be matched). The current study thus provided insight into a factor that is extremely common, but would be challenging to experimentally examine in actual BiCI patients. By manipulating DR of vocoded speech in NH listeners, we were able to directly compare symmetric and asymmetric conditions at various performance levels. The findings in this study elucidate the importance of the poorer ear (demonstrated by reduced binaural unmasking for both symmetric and asymmetric conditions with decreasing DR) as well as degree of interaural asymmetry (demonstrated by reduced unmasking for asymmetric compared to symmetric conditions within a level of DR) on binaural unmasking benefits in BiCI patients. Another original finding was the contralateral interference observed for some participants in the Asymmetric 50% and 35% DR conditions for both Experiment I and Experiment II. This effect has been frequently emphasized in recent papers investigating binaural unmasking in BiCI and SSD-CI users (Bernstein et al., 2016, 2020; Goupell et al., 2018). However, due to the heterogeneity across participants, it extremely difficult to pinpoint factors that contribute to the interference effect. The ability to re-produce this effect in NH listeners using the same paradigm is promising because it opens avenues to isolate and explore different factors that may contribute, which will ultimately help to improve binaural hearing benefits in CI users.

VII. Summary

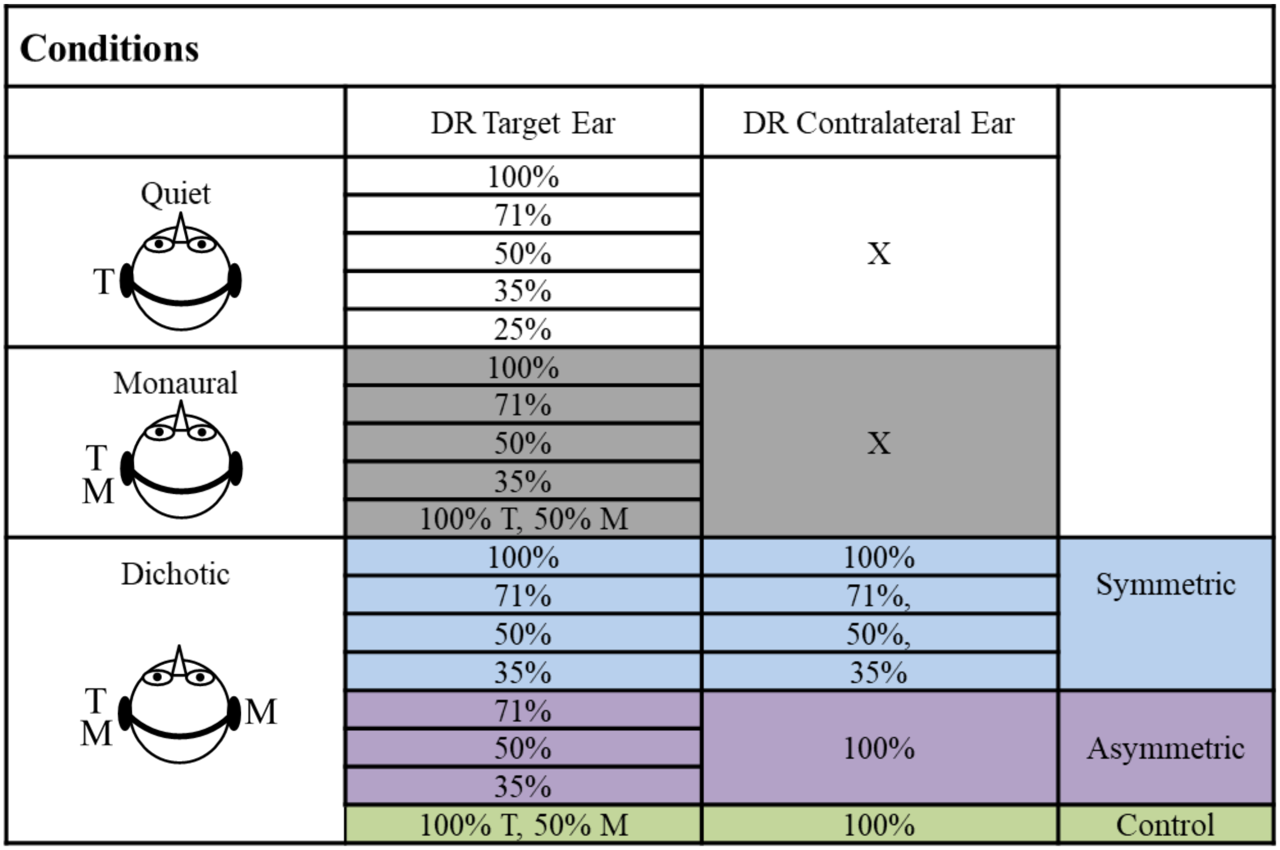
The present study measured speech intelligibility and binaural unmasking in NH individuals listening to vocoded speech to simulate CI processing. Stimulus dynamic range was reduced symmetrically or asymmetrically across ears to investigate the effects of poor and asymmetric temporal envelope encoding in BiCI users. Speech intelligibility declined with decreasing DR in both quiet and masker conditions. Binaural unmasking declined with decreasing DR, and unmasking was greater for symmetric conditions than asymmetric conditions. Further, interaural correlation of masker noise carriers significantly affected results: binaural unmasking was greater for uncorrelated noise carriers than for anti-correlated noise carriers. These results suggest that good temporal envelope encoding is important for speech intelligibility in CI listeners, and indicate that both poor and asymmetric temporal envelope encoding may contribute to the limited binaural unmasking benefit demonstrated by many BiCI users.

Acknowledgements

This research was supported by NIH-NIDCD Grant No. R01DC003083 (to RYL) and NIH-NICHD Grant No. U54HD090256 (to Waisman Center), and funds provided by the University of Wisconsin-Madison Department of Communication Sciences and Disorders to Emily Burg. Portions of this work were presented at the 2019 Conference on Implantable Auditory Prostheses, 2020 Association for Research in Otolaryngology Conference, 2020 Speech in Noise Workshop, and 2021 Conference on Implantable Auditory Prostheses. The authors would like to Shelly Godar for help with participant recruitment and scheduling, Talia Rawitz and Emma Pittman for help with participant recruitment, scheduling, data collection, and data analysis, and the individuals who participated in this study.

VIII. Figures and Tables

Table 1



Conditions			
	DR Target Ear	DR Contralateral Ear	
Quiet T	100%	X	
	71%		
	50%		
	35%		
	25%		
Monaural T M	100%	X	
	71%		
	50%		
	35%		
	100% T, 50% M		
Dichotic T M M	100%	100%	Symmetric
	71%	71%,	
	50%	50%,	
	35%	35%	
	71%	100%	Asymmetric
	50%		
	35%		
	100% T, 50% M	100%	Control

Table 1. Conditions tested in Experiment I.

Figure 1

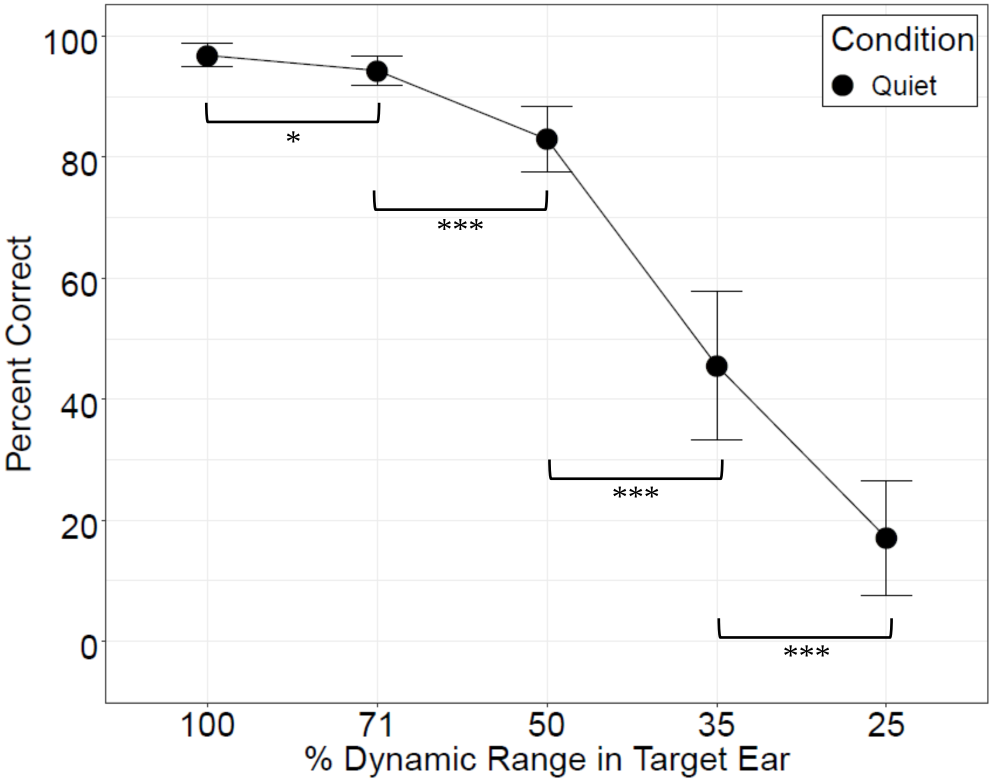


Figure 1. Mean speech intelligibility score measured as percent of correctly repeated words for the Quiet condition as a function of dynamic range. Error bars represent ± one standard deviation. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 2

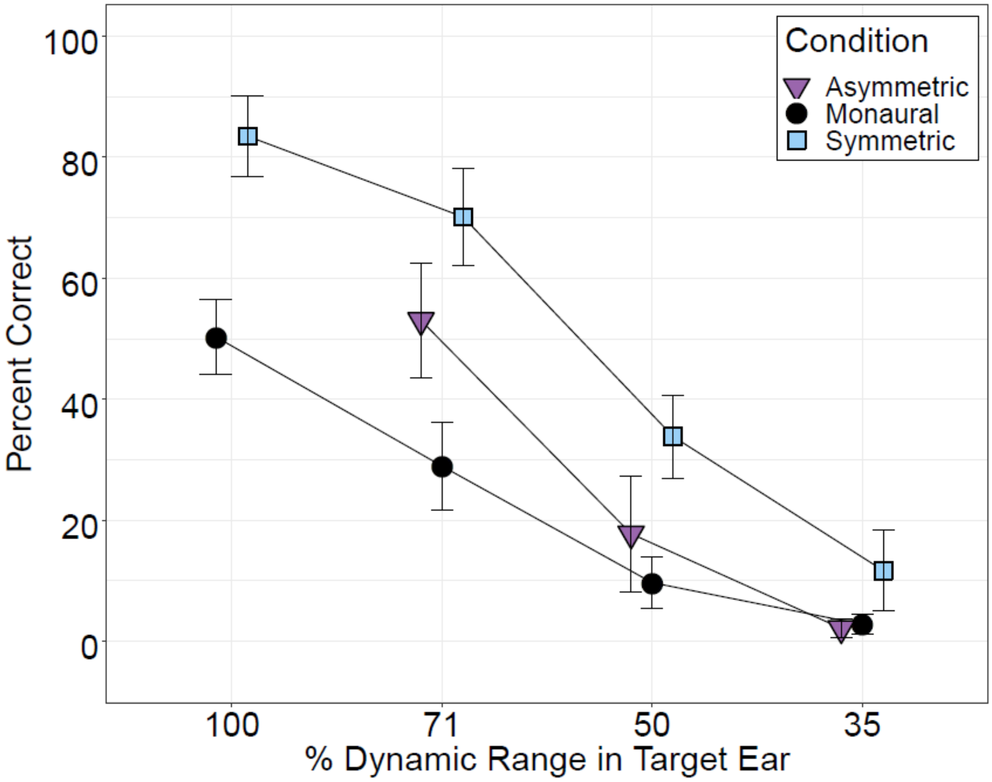


Figure 2. Mean speech intelligibility score measured as percent of correctly repeated words for the masker conditions as a function of dynamic range in the target ear. Error bars represent ± one standard deviation.

Figure 3

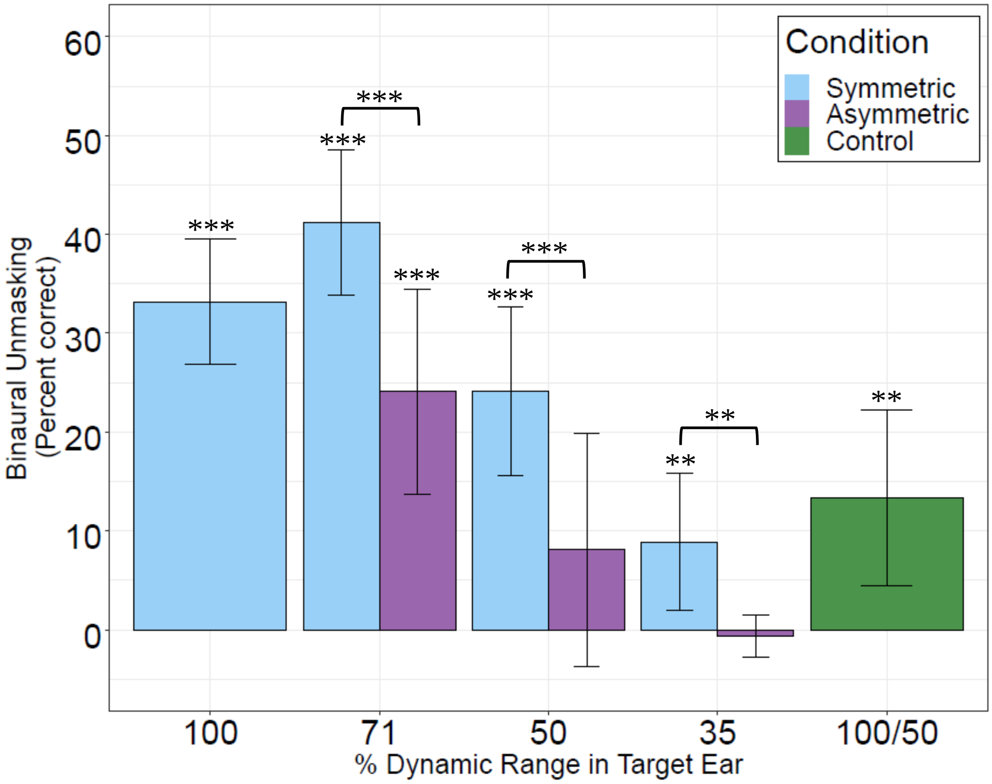
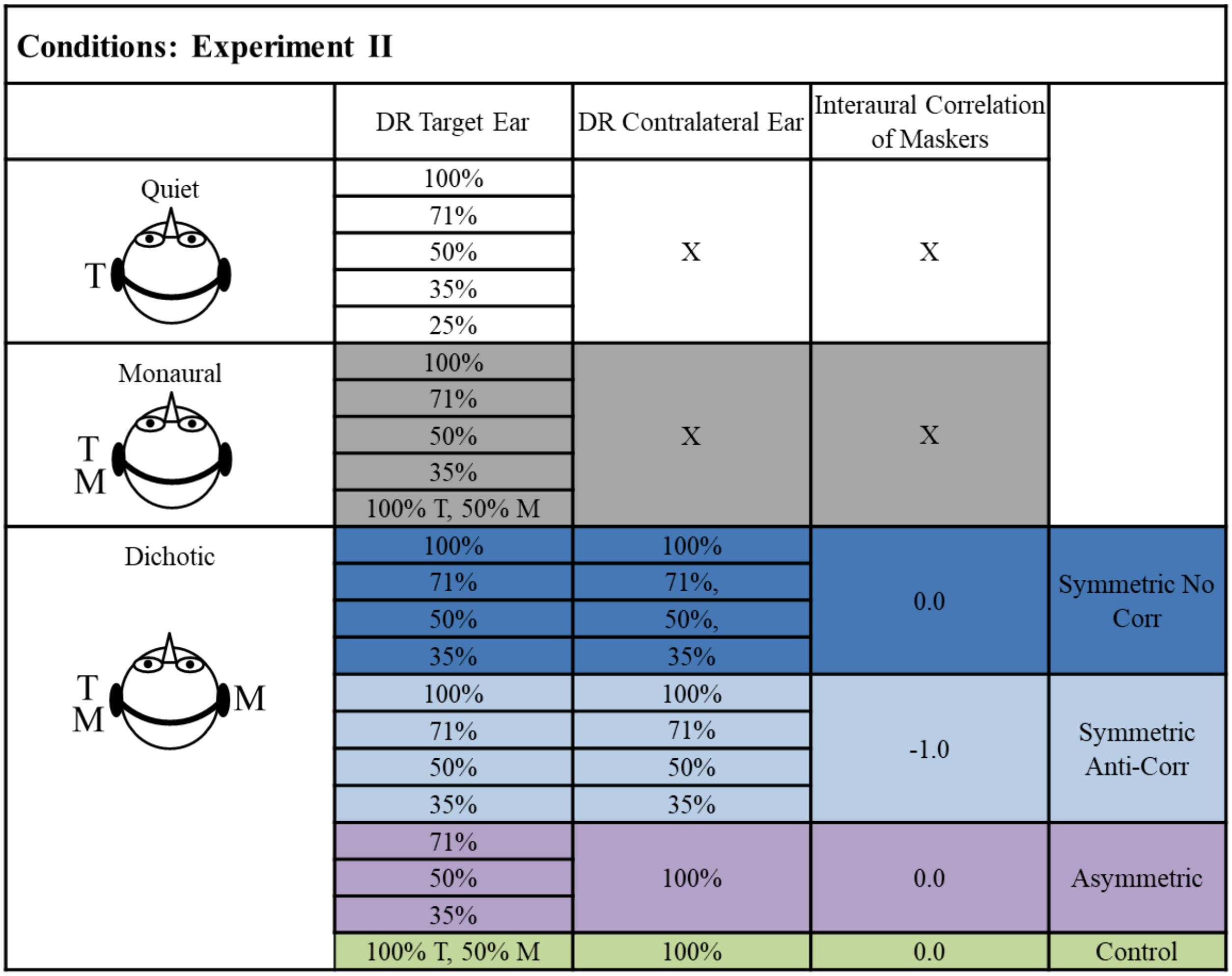


Figure 3. Binaural unmasking measured as improvement in percent correct from the monaural to dichotic configurations for Symmetric, Asymmetric, and Control conditions. Error bars represent ± one standard deviation. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Table 2



Conditions: Experiment II

	DR Target Ear	DR Contralateral Ear	Interaural Correlation of Maskers	
Quiet T	100%	X	X	
	71%			
	50%			
	35%			
	25%			
Monaural T M	100%	X	X	
	71%			
	50%			
	35%			
	100% T, 50% M			
Dichotic T M M	100%	100%	0.0	Symmetric No Corr
	71%	71%,		
	50%	50%,		
	35%	35%		
	100%	100%	-1.0	Symmetric Anti-Corr
	71%	71%		
	50%	50%		
	35%	35%		
	71%	100%	0.0	Asymmetric
	50%			
	35%			
	100% T, 50% M	100%	0.0	Control

Table 2. Conditions tested in Experiment II.

Figure 4

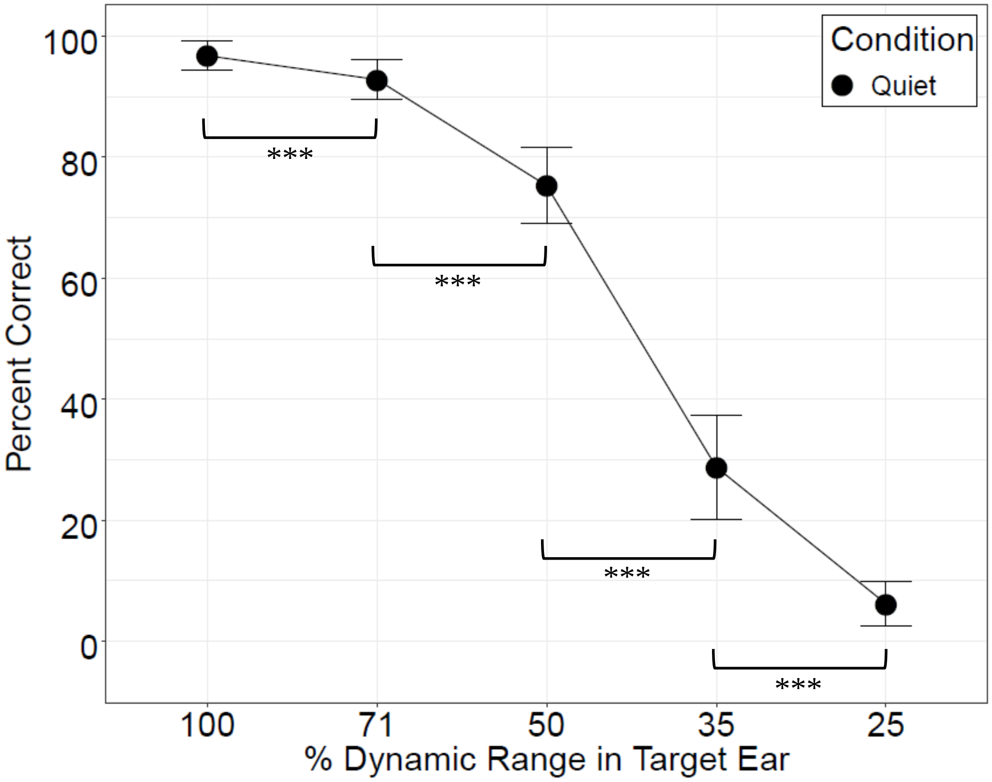


Figure 4. Mean speech intelligibility score measured as percent of correctly repeated words for the Quiet condition as a function of dynamic range. Error bars represent ± one standard deviation. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 5

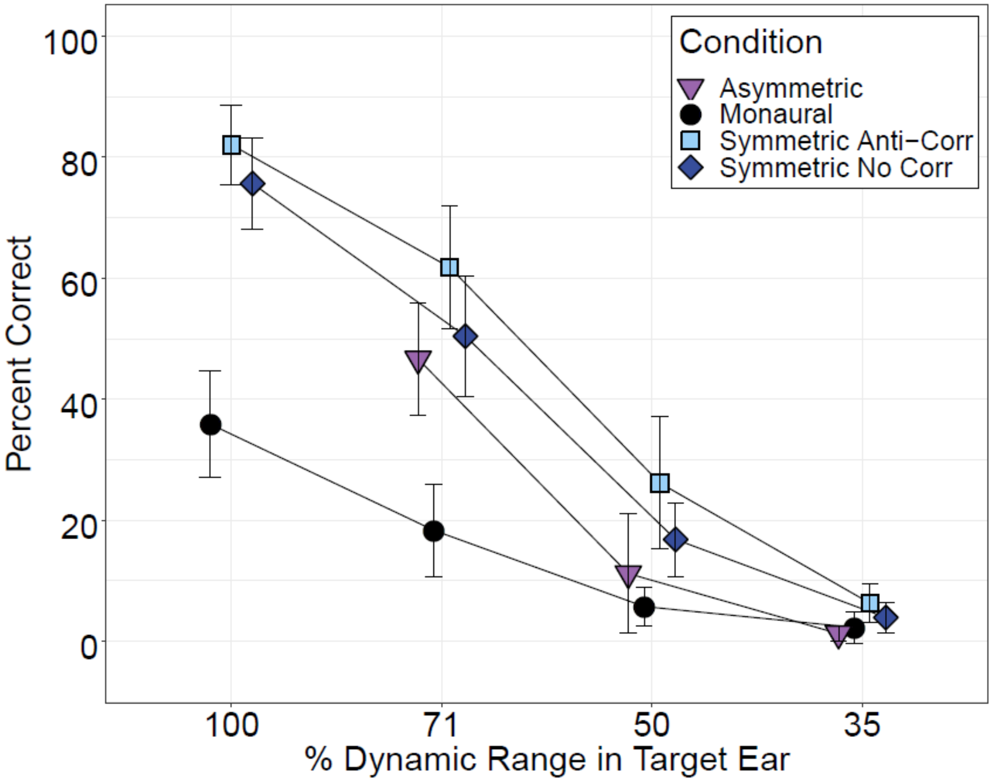


Figure 5. Mean speech intelligibility score measured as percent of correctly repeated words for the masker conditions as a function of dynamic range in the target ear. Error bars represent ± one standard deviation.

Figure 6

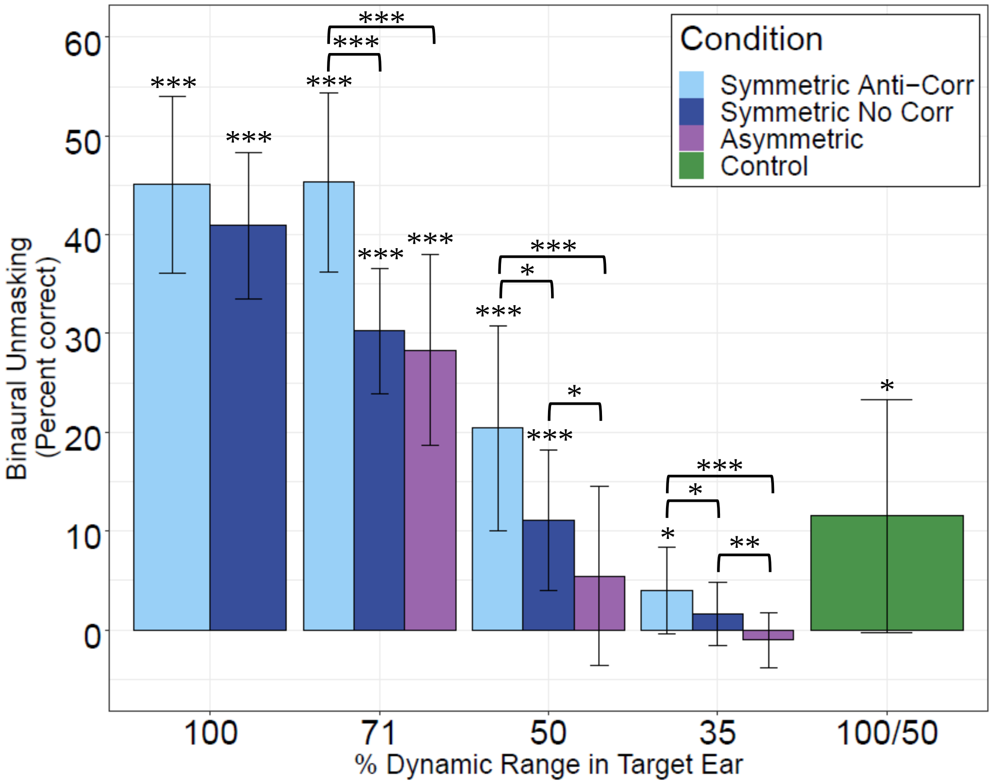


Figure 6. Binaural unmasking measured as improvement in percent correct from the monaural to dichotic configurations for Symmetric Anti-Corr, Symmetric No Corr, Asymmetric, and Control conditions. Error bars represent ± one standard deviation. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

IX. References

ANSI S3.5. (1997). American National Standard: Methods for calculation of the speech intelligibility index. *New York*.

Aronoff, J. M., Shayman, C. S., Prasad, A., Suneel, D., & Stelmach, J. (2015). Unilateral spectral and temporal compression reduces binaural fusion for normal hearing listeners with cochlear implant simulations. *Hearing Research*. https://doi.org/10.1016/j.heares.2014.12.005

Avan, P., Giraudet, F., & Büki, B. (2015). Importance of binaural hearing. *Audiology and Neurotology*. https://doi.org/10.1159/000380741

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bernstein, J. G. W., Goupell, M. J., Schuchman, G. I., Rivera, A. L., & Brungart, D. S. (2016). Having two ears facilitates the perceptual separation of concurrent talkers for bilateral and single-sided deaf cochlear implantees. *Ear and Hearing*, *37*(3), 289–302. https://doi.org/10.1097/AUD.0000000000000284

Bernstein, J. G. W., Stakhovskaya, O. A., Jensen, K. K., & Goupell, M. J. (2020). Acoustic Hearing Can Interfere with Single-Sided Deafness Cochlear-Implant Speech Perception. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000805

Blauert, J., & Butler, R. A. (1985). Spatial Hearing: The Psychophysics of Human Sound Localization by Jens Blauert . *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.392109

Bronkhorst, A. W., & Plomp, R. (1988). The effect of head-induced interaural time and level differences on speech intelligibility in noise. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.395906

Culling, J. F., & Lavandier, M. (2021). Binaural Unmasking and Spatial Release from Masking. In R. Y. Litovsky, M. J. Goupell, R. R. Fay, & A. N. Popper (Eds.), *Binaural Hearing* (pp. 209–241).

Firszt, J. B., Holden, L. K., Skinner, M. W., Tobey, E. A., Peterson, A., Gaggl, W., … Wackym, P. A. (2004). Recognition of speech presented at soft to loud levels by adult cochlear implant recipients of three cochlear implant systems. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000134552.22205.EE

Fu, Q.-J. (2002). Temporal processing and speech recognition in cochlear implant users. *NeuroReport*. https://doi.org/10.1097/00001756-200209160-00013

Gantz, B. J., Tyler, R. S., Rubinstein, J. T., Wolaver, A., Lowder, M., Abbas, P., … Preece, J. P. (2002). Binaural cochlear implants placed during the same operation. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200203000-00012

Goupell, M. J., Kan, A., & Litovsky, R. Y. (2016). Spatial attention in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*, *140*(3), 1652–1662. https://doi.org/10.1121/1.4962378

Goupell, M. J., & Litovsky, R. Y. (2015). Sensitivity to interaural envelope correlation changes in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4904491

Goupell, M. J., Stakhovskaya, O. A., & Bernstein, J. G. W. (2018). Contralateral Interference Caused by Binaurally Presented Competing Speech in Adult Bilateral Cochlear-Implant

Users. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000470

Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. (1999). Speech intelligibility and localization in a multi-source environment. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.424670

Hawley, M. L., Litovsky, R. Y., & Culling, J. F. (2004). The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *The Journal of the Acoustical Society of America*, *115*(2), 833–843. https://doi.org/10.1121/1.1639908

IEEE Recommended Practice for Speech Quality Measurements. (1969). *IEEE Transactions on Audio and Electroacoustics*, *17*(3), 225–246. https://doi.org/10.1109/TAU.1969.1162058

Johansson, M. S. K., & Arlinger, S. D. (2002). Binaural masking level difference for speech signals in noise. *International Journal of Audiology*. https://doi.org/10.3109/14992020209077187

Levitt, H., & Rabiner, L. R. (1967). Predicting Binaural Gain in Intelligibility and Release from Masking for Speech. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1910654

Litovsky, R. Y., & Goupell, M. J. (2021). Binaural Processing of Sounds. In R. Y. Litovsky, M. J. Goupell, R. R. Fay, & A. N. Popper (Eds.), *Binaural Hearing* (pp. 1–8).

Litovsky, R. Y., Goupell, M. J., Misurelli, S. M., & Kan, A. (2017). Hearing with Cochlear Implants and Hearing Aids in Complex Auditory Scenes. In J. Middlebrooks, J. Simon, A. Popper, & R. Fay (Eds.), *The Auditory System at the Cocktail Party* (pp. 261–291). https://doi.org/10.1007/978-3-319-51662-2_10

Litovsky, R. Y., Parkinson, A., & Arcaroli, J. (2009). Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear and Hearing*, *30*(4), 419–431. https://doi.org/10.1097/AUD.0b013e3181a165be

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., & Yu, G. (2004). Bilateral Cochlear Implants in Adults and Children. *Archives of Otolaryngology - Head and Neck Surgery*, *130*(5), 648–655. https://doi.org/10.1001/archotol.130.5.648

Litovsky, R. Y., Parkinson, A., Arcaroli, J., & Sammeth, C. (2006). Simultaneous Bilateral Cochlear Implantation in Adults: A multicenter clinical study. *Ear and Hearing*, *27*(6), 714–731. https://doi.org/10.1097/01.aud.0000246816.50820.42.Simultaneous

Loizou, P. C. (1999). Introduction to cochlear implants. *IEEE Engineering in Medicine and Biology Magazine*. https://doi.org/10.1109/51.740962

Loizou, P. C., Dorman, M. F., & Fitzke, J. (2000). The effect of reduced dynamic range on speech understanding: Implications for patients with cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/00003446-200002000-00006

Loizou, P. C., Hu, Y., Litovsky, R. Y., Yu, G., Peters, R., Lake, J., & Roland, P. (2009). Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3036175

Long, C. J., Carlyon, R. P., Litovsky, R. Y., & Downs, D. H. (2006). Binaural unmasking with bilateral cochlear implants. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-006-0049-4

Long, C. J., Holden, T. A., McClelland, G. H., Parkinson, W. S., Shelton, C., Kelsall, D. C., & Smith, Z. M. (2014). Examining the electro-neural interface of cochlear implant users using psychophysics, CT scans, and speech understanding. *JARO - Journal of the Association for Research in Otolaryngology*, *15*(2), 293–304. https://doi.org/10.1007/s10162-013-0437-5

Lu, T., Litovsky, R. Y., & Zeng, F.-G. (2010). Binaural masking level differences in actual and simulated bilateral cochlear implant listeners. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3290994

Peters, B. R., Wyss, J., & Manrique, M. (2010). Worldwide trends in bilateral cochlear implantation. *Laryngoscope*. https://doi.org/10.1002/lary.20859

Ricketts, T. A., & Kan, A. (2021). Binaural Hearing with Devices. In R. Y. Litovsky, M. J. Goupell, R. R. Fay, & A. N. Popper (Eds.), *Binaural Hearing* (pp. 385–417).

Sayers, B. M., & Cherry, E. C. (1957). Mechanism of Binaural Fusion in the Hearing of Speech. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1914990

Schleich, P., Nopp, P., & D'Haese, P. (2004). Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000130792.43315.97

Spahr, A. J., Dorman, M. F., Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., … Cook, S. (2012). Development and validation of the azbio sentence lists. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31822c2549

Tyler, R. S., Dunn, C. C., Witt, S. A., & Noble, W. G. (2007). Speech perception and localization with adults with bilateral sequential cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31803153e2

van de Par, S., & Kohlrausch, A. (1997). A new approach to comparing binaural masking level differences at low and high frequencies. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.418151

van Hoesel, R., Böhm, M., Pesch, J., Vandali, A., Battmer, R. D., & Lenarz, T. (2008). Binaural speech unmasking and localization in noise with bilateral cochlear implants using envelope and fine-timing based strategies. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.2875229

van Hoesel, R., Ramsden, R., & O'Driscoll, M. (2002). Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. *Ear and Hearing*. https://doi.org/10.1097/00003446-200204000-00006

van Hoesel, R., & Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1539520

Vermeire, K., & Van De Heyning, P. (2009). Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiology and Neurotology*, *14*(3), 163–171. https://doi.org/10.1159/000171478

Wess, J. M., Brungart, D. S., & Bernstein, J. G. W. (2017). The effect of interaural mismatches on contralateral unmasking with single-sided vocoders. *Ear and Hearing*, *38*(3), 374–386. https://doi.org/10.1097/AUD.0000000000000374

Wess, J. M., Spencer, N. J., & Bernstein, J. G. W. (2020). Counting or discriminating the number of voices to assess binaural fusion with single-sided vocoders. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/10.0000511

Whitmer, W. M., Seeber, B. U., & Akeroyd, M. A. (2012). Apparent auditory source width insensitivity in older hearing-impaired individuals. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4728200

Wilson, B. S., & Dorman, M. F. (2007). The surprising performance of present-day cochlear implants. *IEEE Transactions on Biomedical Engineering*. https://doi.org/10.1109/TBME.2007.893505

Wilson, R. H., Hopkins, J. L., Mance, C. M., & Novak, R. E. (1982). Detection and recognition masking-level differences for the individual CID W-1 spondaic words. *Journal of Speech and Hearing Research*. https://doi.org/10.1044/jshr.2502.235

Winn, M. B., Chatterjee, M., & Idsardi, W. J. (2012). The use of acoustic cues for phonetic identification: Effects of spectral degradation and electric hearing. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3672705

Zirn, S., Arndt, S., Aschendorff, A., Laszig, R., & Wesarg, T. (2016). Perception of Interaural Phase Differences with Envelope and Fine Structure Coding Strategies in Bilateral Cochlear Implant Users. *Trends in Hearing*. https://doi.org/10.1177/2331216516665608

Zurek, P. (1993). Binaural advantages and directional effects in speech intelligibility. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical Factors Affecting Hearing Aid Performance*.

CHAPTER V. Investigating Cortical Neural Sensitivity to Changes in Binaural Fusion Caused by Simulated Asymmetric Temporal Resolution

I. Abstract

Individuals with bilateral cochlear implants (BiCIs) experience reduced binaural unmasking compared to normal hearing (NH) listeners, which likely stems in part from interaural asymmetries demonstrated by many BiCI users. Specifically, differences in temporal resolution across ears can result in asymmetric speech performance and poor encoding of binaural cues. To improve binaural outcomes in BiCI users, it is important to understand whether binaural performance in listeners with asymmetries is limited more by the poorer ear, or by the degree of asymmetry across ears. Previous work from our lab investigated the effect of asymmetric temporal resolution on binaural unmasking of speech. We manipulated temporal resolution in NH listeners by compressing the dynamic range (DR) of vocoded speech symmetrically and asymmetrically across ears. Compressing DR reduces amplitude modulations in the speech envelope, thus reducing the fidelity of temporal information (i.e., temporal resolution). We found that binaural unmasking of speech was limited more by asymmetry than performance of the poorer ear, and posited that this may have been due to reduced fusion of asymmetric stimuli.

To better understand mechanisms underlying these behavioral unmasking results, the present study investigated the effect of interaural asymmetries in temporal resolution on binaural fusion, a prerequisite for binaural unmaking, in normal hearing listeners using a subjective rating scale and the cortically generated acoustic change complex (ACC). The ACC is elicited by a change in an ongoing auditory stimulus, such as a change in the degree of binaural fusion. Binaurally presented uncorrelated speech shaped noise (SSN), which is perceptually diffuse in the head, was changed to 20 Hz amplitude modulated (AM) SSN. DR was varied symmetrically and asymmetrically to create differences in temporal resolution across ears. A third condition in which uncorrelated SSN was changed to correlated SSN was also included to replicate previous

findings that changes to interaural correlation (and fusion) can elicit the ACC. We hypothesized that greater similarity in stimuli across ears would result in a higher subjective rating of fusion and larger ACC magnitude. Results from the subjective measure of fusion are consistent with our hypothesis: The Correlated SSN condition was rated as the most fused, and the Symmetric DR condition was rated as significantly more fused than the Asymmetric DR condition. Consistent with subjective ratings, the Correlated SSN condition elicited the largest ACC magnitude. However, the perceived difference in fusion between Symmetric and Asymmetric DR conditions was not reflected in the neural responses. This may have been due to the fact that the difference in fusion between Symmetric and Asymmetric DR conditions was not salient enough to elicit a significant difference in ACC magnitude.

II. Introduction

Binaural hearing refers to the ability to integrate bilateral acoustic input, and enables listeners to identify the location of sounds, and perceptually organize complex auditory environments (for review, see Akeroyd, 2006). These skills are important for safety (e.g., identifying the location of an approaching car), and for communication in the noisy environments that humans frequently experience. The binaural system is able to accomplish these tasks by precisely comparing differences in the timing and level of sounds arriving at each ear, referred to as binaural cues (Middlebrooks & Green, 1991). Normal hearing (NH) listeners are able to make excellent use of these cues to accurately localize sounds and perceptually separate a speaker of interest in the presence of background noise (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Hawley, Litovsky, & Colburn, 1999; Hawley, Litovsky, & Culling, 2004; Mills, 1958). In situations where a target speaker and an interfering talker are spatially separated, listeners are able to better understand the speech of interest by attending to the ear that is closer to the target. This is a result of a higher signal-to-noise ratio at the ear that is closer to the target speech due to attenuation of the interfering sound as it travels around the head (Hawley et al., 1999, 2004), and is known as the “better ear effect.” However, this benefit relies on the interferer(s) being asymmetrically separated relative to the target. In the real-world, interfering sounds frequently arise from both sides of the head, reducing or eliminating the benefit of better-ear listening (Hawley et al., 2004). It is in these complex situations that listeners must take advantage of binaural cues, such as interaural timing and level differences, to perceptually separate the target from interfering sounds. This benefit of binaural processing is known as binaural unmasking, or squelch (Hawley et al., 2004).

Individuals with hearing loss are at a distinct disadvantage when verbally communicating in complex environments due to reduced audibility of auditory information. Hearing aids can improve audibility of speech and acoustic cues for individuals with usable acoustic hearing. Up until the 1970s, it was typical for clinicians to recommend a unilateral hearing aid, even to patients with bilateral hearing loss. Since that time, the importance of binaural hearing for communication in noisy environments has been established, and the current clinical standard is to recommend bilateral hearing aids to patients with hearing loss in both ears (for review, see Ricketts & Kan, 2021). However, not all patients with hearing loss are able to achieve equal benefit from hearing aids. Some patients with significant sensorineural hearing loss in the severe-to-profound range obtain little to no benefit from acoustic amplification. For example, even with properly fitted hearing aids, some still report difficulty understanding speech in quiet environments. These patients may qualify to receive a cochlear implant (CI), which is an implantable auditory device that by-passes the peripheral auditory system, enabling patients to hear via electrical stimulation of the auditory nerve (Ricketts & Kan, 2021).

CIs have undergone significant advancements since their invention (for a historical review, see Wilson, 2019) and now enable many patients to achieve adequate speech understanding (>80%) in quiet (Firszt et al., 2004; Wilson & Dorman, 2007). However, CI patients frequently report difficulty listening and communicating in noisy environments. Thus, there is a clinical incentive to investigate the potential benefits of bilateral CIs (BiCIs) in order to improve performance. Compared to unilateral CI, many patients with BiCIs demonstrate improved speech perception in noise (e.g., Gantz et al., 2002; Litovsky et al., 2004; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006; Loizou et al., 2009; Schleich, Nopp, & D'Haese, 2004; Tyler, Dunn, Witt, & Noble, 2007; van Hoesel, Ramsden, & O'Driscoll, 2002; van Hoesel &

Tyler, 2003). However, the literature suggests that improvements are predominantly due to the better ear effect (i.e., listeners can attend to the ear closer to the target), which does not necessitate binaural processing (Gantz et al., 2002; Litovsky et al., 2006; Schleich et al., 2004; van Hoesel et al., 2002; van Hoesel & Tyler, 2003). In fact, many studies have found weak or absent evidence of binaural unmasking benefit in BiCI users (e.g., Gantz et al., 2002; Goupell et al., 2016, 2018; Loizou et al., 2009; Schleich et al., 2004; van Hoesel et al., 2008). It is imperative to understand the mechanisms underlying impaired binaural processing in these patients in order to guide research in device design, surgical techniques, and clinical intervention, and ultimately improve patient outcomes.

In Chapter IV of this dissertation, we hypothesized that reduced binaural unmasking benefit in BiCI users may be related to poor delivery and encoding of temporal envelope information, which BiCI users rely on for speech understanding due to the lack of fine structure information conveyed by the speech processors (Loizou, 1999). Additionally, we hypothesized that interaural asymmetries in temporal resolution may further hinder binaural integration and unmasking due to reduced binaural fusion of the maskers, making it more difficult for listeners to perceptually separate monaurally presented target speech from diotically presented interfering speech (Aronoff, Shayman, Prasad, Suneel, & Stelmach, 2015; Bernstein, Goupell, Schuchman, Rivera, & Brungart, 2016; Goupell et al., 2018). We measured binaural unmasking of vocoded speech in NH listeners with symmetrically and asymmetrically reduced dynamic range (DR) to simulate poor and asymmetric temporal resolution, respectively. Similar to a CI, vocoders discard fine structure information and relay information for speech understanding in the temporal envelope. Reducing the DR of a vocoded speech signal decreases the depth of amplitude modulations in the envelope, making the speech more difficult to understand (Loizou, Dorman,

& Fitzke, 2000). Our results supported both of our hypotheses- binaural unmasking of vocoded speech declined with decreasing DR, and asymmetric reductions in DR negatively impacted binaural unmasking more than symmetric reductions. While not directly tested in this study, our theory that interaural asymmetries impact binaural fusion is supported by previous work that has shown decreased binaural fusion of speech in NH listeners with asymmetric spectral compression using bilateral vocoders (Aronoff et al., 2015), and interaural frequency mismatch using single-sided vocoders (Wess, Spencer, & Bernstein, 2020).

Due to the number of recent studies suggesting that binaural unmasking in CI users with interaural asymmetry may be hindered by inadequate binaural fusion (Bernstein et al., 2016; Bernstein, Iyer, & Brungart, 2015; Bernstein, Stakhovskaya, Jensen, & Goupell, 2020; Goupell et al., 2018; Wess, Brungart, & Bernstein, 2017; Wess et al., 2020), this topic warrants further investigation. Binaural fusion refers to the perception of one unified sound when signals presented to each ear are correlated (Sayers & Cherry, 1957). As interaural correlation (IC) decreases, the perceived spatial width of the sound increases. At very low ICs the spatial width of the sound may be so great that the listener may perceive multiple sounds (Whitmer, Seeber, & Akeroyd, 2012). NH listeners demonstrate high sensitivity to IC of acoustic fine structure as well as the envelope (Lu, Litovsky, & Zeng, 2010; van de Par & Kohlrausch, 1997). BiCI listeners, on the other hand, demonstrate a lesser degree of sensitivity to interaural envelope correlation (Goupell & Litovsky, 2015; Long, Carlyon, Litovsky, & Downs, 2006; Lu et al., 2010). This may be due to an inherent lack of IC in BiCI users resulting from differential delivery and encoding of the temporal envelope across ears (Goupell & Litovsky, 2015). Consequently, this could affect binaural fusion in BiCI users, since fusion is tightly coupled to IC (Fitzgerald, Kan, & Goupell, 2015; Whitmer et al., 2012).

Numerous subjective methods have been employed to measure binaural fusion, including: (1) an alternative choice of fused/unfused (Aronoff et al., 2015; Suneel, Staisloff, Shayman, Stelmach, & Aronoff, 2017), (2) a sliding perceptual scale ranging from a single punctate sound to two separate sounds (Suneel et al., 2017), (3) having listeners categorically select a picture that best represented what they heard (Fitzgerald et al., 2015; Goupell, Stoelb, Kan, & Litovsky, 2013; Kan, Stoelb, Litovsky, & Goupell, 2013), (4) asking listeners to sketch the perceived size of a sound on a head either from the front or top perspective (Blauert & Lindemann, 1986; Whitmer et al., 2012), (5) asking listeners to count how many sounds they heard (Francart, Wiebe, & Wesarg, 2018; Kan et al., 2013). While these subjective methods may be valid measures of binaural fusion in NH listeners, the concept of fusion may be abstract to CI users who experience intrinsic interaural decorrelation (Fitzgerald et al., 2015). Wess et al. (2020) sought to validate a more objective measure of binaural fusion for CI users using speech stimuli. To simulate CI listening for patients with single sided deafness (SSD-CI) in NH participants, they presented a mixture of unprocessed speech to one ear and vocoded copies of the speech with varying degrees of spectral mismatch to the opposite ear. Listeners were either asked to report how many voices they heard, or identify which of two stimulus options contained a bilaterally presented speech signal. When tasked with counting the number of voices, results demonstrated that NH listeners generally reported the bilaterally presented speech as two separate voices, regardless of interaural frequency mismatch. In contrast, when listeners were asked to identify the stimulus in which the speech signal was presented bilaterally, listeners were better at identifying the correct stimulus when there was no interaural mismatch (Wess et al., 2020). As suggested by the authors, these contrasting results emphasize how difficult it can be to measure binaural fusion subjectively, even in NH listeners. Further, they proposed that the contradictory results across tasks indicate that listeners may have experienced partial fusion, but were unable to verify this due to the nature of the task (Wess et al., 2020).

A method for the objective assessment of binaural fusion is sorely needed due to the difficulty in measuring binaural fusion subjectively, specifically when there are asymmetries across ears or when listeners experience incomplete or partial fusion. The measure of auditory evoked potentials (AEPs), specifically, the acoustic change complex (ACC) may be a promising avenue to explore. Studies investigating the neural basis of binaural hearing have shown that information from the two ears is initially integrated in the superior olivary complex of the brainstem, and that integration of binaural input continues up to the cortex (Moore, 1991). The ACC is a cortical auditory evoked potential elicited by a change in an ongoing auditory stimulus (Martin & Boothroyd, 1999). This evoked potential is characterized by the N1-P2 waveform, and is thought to reflect the cortical neural processing underlying auditory discrimination ability (He, Grose, & Buchman, 2012). The ACC can be elicited by a change to numerous different aspects of a stimulus, including intensity (Martin & Boothroyd, 2000), frequency (Harris, Mills, He, & Dubno, 2008), periodicity (Martin & Boothroyd, 1999), interaural correlation (Chait, Poeppel, De Cheveigné, & Simon, 2005; Chait, Poeppel, & Simon, 2007; Jones, Pitman, & Halliday, 1991), and amplitude modulation depth (Han & Dimitrijevic, 2015). While the ACC is not a direct measure of perception, there is accumulating evidence to suggest that the ACC is correlated with behavioral sound discrimination. For example, Ross et al. (2007) measured interaural phase difference detection in young, middle, and older listeners, and found that interaural phase differences elicited ACCs for frequencies at which participants showed behavioral sensitivity, but not for frequencies beyond the cutoff for behavioral detection. ACC amplitude has also been shown to increase with increasing magnitude of the acoustic change (e.g., Dimitrijevic, Michalewski, Zeng, Pratt, & Starr, 2008; Han & Dimitrijevic, 2015; Harris et al., 2008; He et al., 2012; Martin & Boothroyd, 2000). Additionally, the ACC shows excellent test-retest reliability (Tremblay, Friesen, Martin, & Wright, 2003) and, importantly, can be recorded in individuals who use CIs (e.g., Martin, 2007).

The present study sought to investigate the impact of asymmetric DR on binaural fusion in NH listeners using both subjective and objective measures. The goals of this study were twofold: (1) examine the effect of interaural asymmetry on perceived binaural fusion using a behavioral rating scale, and (2) investigate whether the ACC is useful for examining cortical neural sensitivity to differences in binaural fusion between AM noise with symmetric and asymmetric DR. Given that the ACC can be elicited by changes in binaural fusion, we hypothesized that greater similarity in stimuli across ears in the Symmetric DR condition would result in greater subjective fusion ratings and larger ACC responses compared to the asymmetric DR condition.

III. Methods

A. *Participants*

20 young NH adults (18 females and 2 males; age range 18-29 years) took part in the electrophysiologic portion of the experiment. 14 young NH adults (13 females and 1 male; age range 19-24 years) took part in the behavioral portion of the experiment. To be eligible for the study, all participants were required to pass a hearing screening at 20 dB HL at octave frequencies from 250-8000 Hertz.

B. *Stimuli*

a. Electrophysiologic Measure

Stimuli were digitally generated in MATLAB (v2016b; Mathworks, MA, USA) at a sampling rate of 44.1 kHz. Stimuli consisted of speech-shaped noise (SSN) that was spectrally matched to a female-talker AzBio sentence corpus. We chose to spectrally match stimuli for the present study to the AzBio corpus in order to facilitate comparisons between the present study and the binaural unmasking experiment detailed in Chapter IV. Because the ACC is potentially elicited by any discriminable change in an auditory stimulus, we could not employ speech stimuli in the present study because transitions in the speech (e.g., syllable transitions, formant transitions, etc.) can elicit multiple, overlapping ACCs (Martin & Boothroyd, 2000; Ostroff, Martin, & Boothroyd, 1998). Therefore, we aimed to replicate as many features of the stimuli used in Chapter IV as possible, while also ensuring our stimuli were suitable for measuring AEPs. One stimulus sweep was 3000 ms in length. The first 1500 ms consisted of unmodulated SSN, and the second 1500 ms consisted of either unmodulated SSN or 20 Hz amplitude modulated (AM) SSN (Figure 1). The dynamic range of the AM portion was either maintained at 100% (no compression) or decreased to 50% DR to reduce temporal resolution. Stimuli were RMS equalized to -28 dB in MATLAB and then calibrated using an ear simulator (Bruel & Kjaer; 4157, Denmark) to 70 dB SPL. Sweeps were continuously presented so that stimuli alternated between unmodulated SSN and AM SSN.

b. Behavioral Measure

Stimuli for the behavioral measure were the same as those used for the electrophysiologic measure. The only difference was that stimuli were not presented in an alternating paradigm. Instead, stimulus sweeps were presented as individual trials.

C. Conditions

a. Electrophysiologic Measure

Participants were tested in three binaural and three monaural conditions. Binaural conditions included a Symmetric DR, Asymmetric DR, and Correlated SSN condition (Table 1). The Symmetric DR condition alternated between 1500 ms of unmodulated SSN that was uncorrelated across ears, and 1500 ms of 20 Hz AM SSN with a DR of 50% in each ear. The SSN carriers remained uncorrelated throughout the duration of the AM portion. The Asymmetric DR condition alternated between 1500 ms of unmodulated SSN that was uncorrelated across ears, and 1500 ms of 20 Hz AM SSN with a DR of 50% in the left ear, and a DR of 100% in the right ear. Consistent with the Symmetric condition, the SSN carriers remained uncorrelated throughout the duration of the AM portion of the stimuli. The Correlated SSN condition was included to replicate previous findings that an increase in interaural correlation of unmodulated noise elicits an ACC (Jones et al., 1991). In this condition, stimuli alternated between 1500 ms of unmodulated, uncorrelated SSN (IC = 0) and 1500 ms of unmodulated, correlated SSN (IC = 1) (Figure 1). The binaural conditions provided different amounts of IC either in the envelope of the AM portion (Symmetric and Asymmetric DR conditions) or in the fine structure (Correlated SSN condition), which has been shown to affect binaural fusion (Aronoff et al., 2015; Chait et al., 2005; Jones et al., 1991; Wess et al., 2020). Previous work has demonstrated that both behavioral and cortical neural sensitivity to changes in IC differ depending on the direction of the fusion change, with the fused to unfused direction eliciting better sensitivity than the unfused to fused direction (e.g., Chait et al., 2005). We chose to use an alternating stimulus paradigm in order to examine ACCs for both directions of change. Previous work has shown that an ACC can be elicited by the addition of AM to noise stimuli, with larger AM depths (i.e. greater DRs), evoking larger ACC amplitudes (Han & Dimitrijevic, 2015). Thus, we reasoned that the Asymmetric DR condition could elicit a larger ACC than the Symmetric DR condition simply due to the 100% DR stimulus presented to the right ear, which was a larger acoustic change from unmodulated SSN than 50% DR. The monaural conditions were included in order to measure ACCs elicited by AM with different DRs, independent of fusion, and to compare ACCs for the left and right ear using the same stimulus. Stimuli changed every 1500 ms (i.e., diffuse-fused-diffuse for binaural conditions; unmodulated-AM-unmodulated for monaural conditions), resulting in two ACCs for every 3000 ms stimulus sweep (Figure 1). 1500 ms of unmodulated, uncorrelated SSN was alternated with experimental stimuli for all conditions, and will be referred to as the reference (ref) stimulus.

b. *Behavioral Measure*

Binaural fusion was subjectively assessed for the three binaural conditions tested in the electrophysiologic study. A fourth condition in which the second 1500 ms of the stimulus remained uncorrelated (i.e., 1500 ms uncorrelated SSN followed by 1500 ms uncorrelated SSN) was included in order to gauge degree of fusion for the reference stimulus in the binaural conditions (Table 2). Each trial consisted of one stimulus sweep.

D. *Equipment and procedure*

a. *Electrophysiologic Measure*

Testing took place in the Child Hearing Lab (PI: Dr. Viji Easwar) at the University of Wisconsin-Madison. Participants reclined in a comfortable chair located in a darkened, double-walled sound attenuating booth and watched a silent movie during testing. Participants were instructed to stay awake during testing and to remain as still as possible during stimulus presentation to prevent movement artifacts. A computer with customized software written in MATLAB was used to play stimuli to ER10X insert earphones secured in participants ears with rubber tips of appropriate size and Westone Silicast putty. Evoked potentials were recorded using a three-channel Intelligent Hearing Systems OptiAmp EEG system with a bandpass filter of 1-5000 Hz, and amplification gain of 100,000. Analog to digital conversion of the data was completed using a computer equipped with an RME Fireface UFX+ at a sampling rate of 96,000 Hz. The non-inverting electrode was placed on the vertex of the head (Cz), reference electrodes were placed on each mastoid, and the ground electrode was placed on the left collarbone with skin prepping paste and conductive electrode gel. The reference electrodes on each mastoid were linked with a jumper cable. Electrode impedances were maintained below 5 kΩ with inter-electrode differences below 2 kΩ. Potentials were recorded using alternating polarity, and 300 stimulus sweeps were collected per condition.

b. Behavioral Measure

Participants were seated in a double-walled sound attenuating booth in front of a computer screen and mouse. A computer with customized software written in MATLAB was used to create the participant interface and deliver stimuli. Stimuli were played to Etymotic ER-2 insert earphones through a Tucker-Davis Technologies System III. Participants were instructed to press the play button, listen to the stimulus, and select the picture that most accurately represented what they heard. The fusion scale was a collection of six pictures depicting varying degrees of binaural fusion ranging from one centered punctate sound, to one large/diffuse sound, to two separate punctate sounds (Figure 2). Participants were instructed to rate only the second half of the stimulus (last 1500 ms), and to focus on how spatially large or small the sound(s) were. Since the modulated conditions had a very distinct sound quality from the Correlated SSN condition, participants were told to ignore any differences in sound quality across trials and to only focus on the perceived size of the sound(s). Participants were allowed to repeat each stimulus as many times as needed before selecting done and moving on to the next trial. The visual fusion scale utilized in the present study was previously employed by Suneel et al. (2017) to measure binaural fusion of interaurally mismatched vocoded speech in NH adults. Condition order was randomized, and 30 trials were run per condition.

E. Electrophysiologic Data Analysis

Electrophysiologic data were low pass filtered at 15 Hz and separated into individual epochs corresponding to one stimulus sweep (3000 ms). Each stimulus sweep was further separated into two 1500 ms epochs corresponding to the two ACCs. These epochs underwent interquartile range (IQR) based artifact rejection separately (rejection thresholds = first quartile-1.5*IQR; third quartile+1.5*IQR). Following artifact rejection, alternating polarities were averaged together. N1 waves typically occur around 125 ms post stimulus onset or change, and P2 waves typically occur around 200 ms post stimulus onset or change, thus, the response window was defined by these typical latencies ±50ms: 75-250 ms post stimulus change (Picton et al., 2000). This window was confirmed to contain the change complex for both ACCs by visually examining the grand average waveforms (Figure 5). The simplest method for analyzing AEP data is to “pick the peaks,” where the point of maximum negative voltage near 125 ms post stimulus onset or change is labeled as N1 and the maximum positive voltage near 200 ms post stimulus onset or change is labeled as P2. However, even when peak picking is completed by expert examiners, there is still a level of subjectivity present. Additionally, some participants may have smaller responses and/or nosier waveforms than others, making it difficult to distinguish true responses from noise (Picton et al., 2000). This can result in missing data if a response does not have clear N1-P2 morphology. Due to these disadvantages, we employed an alternative method, which was to measure the area under the curve (AUC) during the response window. This method does not require subjective peak-peaking and prevents data from being excluded from analysis. AUC was computed for each condition by taking the trapezoidal integration of the absolute-valued waveform amplitude in the response window. Thus, the AUC measure encompassed the area of both positive and negative peaks in the response window. ACC area measures have been shown to produce comparable results to peak-to-peak amplitude measures (e.g., Niemczak & Vander Werff, 2019).

F. Statistical analysis

a. Behavioral Measure

The effect of interaural asymmetry on perceived binaural fusion was evaluated using a one-way repeated measure analysis of variance (RM ANOVA) with condition as the independent variable (four levels: Correlated SSN, Symmetric DR, Asymmetric DR, Uncorrelated SSN) and behavioral fusion rating as the dependent variable. Assumptions for omnibus and post-hoc tests were statistically evaluated using Mauchly’s test of Sphericity and Shapiro-Wilk normality tests. Post-hoc pairwise comparisons were completed using paired t-tests for normally distributed data, and Wilcoxon Signed Rank tests for non-normally distributed data. Benjamini-Hochberg corrections were employed to control false discovery rate (Benjamini & Hochberg, 1995). Alpha level was set to 0.05.

b. *Electrophysiologic Measure*

The effect of interaural asymmetry on cortical neural sensitivity to changes in binaural fusion was examined using a two-way RM ANOVA with condition (three levels: Symmetric DR, Asymmetric DR, Correlated SSN) and direction of change (two levels: ACC 1- change *to* ref, ACC 2- change *from* ref) as the independent variables, and AUC magnitude as the dependent variable. Pairwise comparisons between monaural conditions were conducted to examine the effect of ear (50% Left vs. 50% Right) and DR (50% Right vs. 100% Right) on AUC magnitude. Assumptions for omnibus and pairwise tests were statistically evaluated using Mauchly's test of Sphericity and Shapiro-Wilk normality tests. Post-hoc pairwise comparisons and planned comparisons were completed using paired t-tests for normally distributed data, and Wilcoxon Signed Rank tests for non-normally distributed data. Benjamini-Hochberg corrections were employed to control false discovery rate (Benjamini & Hochberg, 1995). Alpha level was set to 0.05.

IV. Results

A. *Effect of Interaural Asymmetry on Subjective Ratings of Binaural Fusion*

Histograms plotting the frequency of times each level of the fusion scale was selected for each condition are shown in Figure 3. Participants most frequently rated the Correlated SSN condition as level 2 (one sound). The Uncorrelated SSN condition was most frequently rated as level 3 (a single sound perceived as slightly larger in size than level 2). Responses for Symmetric DR and Asymmetric DR conditions are shifted more towards higher levels of the scale, indicating less fusion. The Symmetric DR condition was most frequently rated as level 4 (one very large or diffuse sound), but was also frequently rated as level 5 (two separate sounds, but perceived somewhat centrally). The Asymmetric DR condition was most frequently rated as level 4 and 5 (the number of responses was almost equal for these levels), but was also frequently rated as level 6 (two punctate sounds, one at each ear). Average fusion ratings for each condition are plotted in Figure 4. On average, the Correlated SSN condition elicited the lowest scale rating (mean ± standard deviation=2.3±0.7), indicating the highest degree of fusion, followed by the Uncorrelated SSN condition (3.5±0.7), Symmetric DR condition (4.2±0.4), and finally the Asymmetric DR condition (4.6±0.6). A one-way RM ANOVA, using a Greenhouse-Geisser correction for a violation of sphericity, revealed a significant main effect of condition on fusion rating [$F(3,39)=36.9$, $p<0.001$]. Post-hoc pairwise comparisons revealed that the Correlated SSN condition was perceived as being significantly more fused than the other three conditions (Uncorrelated SSN: $p<0.01$; Symmetric and Asymmetric DR: $p<0.001$). condition ($p<0.001$), Symmetric DR condition (p<0.001), and Asymmetric DR condition ($p<0.001$). Further, the Uncorrelated SSN condition was perceived as being significantly more fused than Symmetric and Asymmetric DR conditions ($p<0.001$ for both comparisons). Consistent with our hypothesis, the Symmetric DR condition was rated as significantly more fused than the Asymmetric DR condition ($p<0.001$).

B. Effect of Interaural Asymmetry on ACC Response Magnitude

AUC magnitude for each binaural condition is plotted in Figure 6. ACC 1 represents the change from the condition stimulus to the reference stimulus (i.e., change to reference), and ACC 2 represents the change from the reference stimulus to the condition stimulus (i.e., change from reference). Response patterns were similar for ACC 1 and ACC 2, with the Correlated SSN condition eliciting the largest response (ACC 1: 0.33±0.12; ACC 2: 0.23±0.10), followed by the Asymmetric DR condition (ACC 1: 0.17±0.08; ACC 2: 0.14±0.05), and then the Symmetric DR condition (ACC 1: 0.14±0.06; ACC 2: 0.12±0.06). A two-way RM ANOVA, using a Greenhouse-Geisser correction for the Condition factor due to a violation of sphericity, revealed significant main effects of condition [F(2,38)=37.3, $p<0.001$] and direction of change [F(1,19)=32.8, $p<0.001$] on AUC magnitude, as well as a significant interaction between condition and direction of change [F(2,38)=7.8, $p<0.01$]. Post-hoc pairwise comparisons revealed that AUC magnitude for the Correlated SSN condition for ACC 1 (change to ref) was significantly greater than the Symmetric and Asymmetric DR conditions ($p<0.001$ for both comparisons). Similarly, AUC magnitude for the Correlated SSN condition for ACC 2 (change from ref) was significantly greater than the Symmetric ($p<0.001$) and Asymmetric ($p<0.01$) DR conditions. AUC magnitude for Symmetric and Asymmetric DR conditions did not differ significantly for either direction of change ($p>0.05$ for all comparisons). The effect of change direction (i.e., change to ref vs. change from ref) was evaluated by comparing AUC magnitudes for ACC 1 and ACC 2. Correlated SSN AUC magnitude was significantly greater for ACC 1 (change to ref) than ACC 2 (change from ref). Symmetric and Asymmetric DR responses did not differ significantly between ACC 1 and ACC 2.

The AUC for each monaural condition is plotted in Figure 7. For ACC 1 (change to ref), the Monaural 100% Right condition elicited the largest AUC magnitude (0.16±0.06), followed by the Monaural 50% Right condition (0.13±0.05), and then the Monaural 50% Left condition (0.11±0.05). Pairwise comparisons revealed a significant difference between 50% Right and 100% Right conditions ($p<0.05$), and no significant difference between 50% Right and 50% Left conditions ($p>0.05$). This indicates that presentation ear did not significantly affect ACC 1 responses, and that 100% DR elicited a larger ACC than 50% DR. For ACC 2 (change from ref), Monaural 100% Right and Monaural 50% Left conditions elicited similar AUC magnitudes (100% Right: 0.11±0.04; 50% Left: 0.11±0.04), and responses for these conditions were larger than the Monaural 50% Right condition response (0.08±0.04). Pairwise comparisons revealed that the 100% Right condition elicited significantly larger AUC magnitude than the 50% Right condition ($p<0.01$), consistent with ACC 1 results. In contrast to ACC 1, the 50% Left condition elicited a significantly larger response than the 50% Right condition ($p<0.05$), indicating that presentation ear significantly affected AUC magnitude for ACC 2 responses. Comparison of ACC 1 and ACC 2 responses revealed that AUC magnitudes for the 100% Right and 50% Right conditions were significantly larger for ACC 1 than ACC 2 (100% Right: $p<0.01$; 50% Right: $p<0.001$), indicating that the direction of the change significantly affected response magnitude.

V. Discussion

The present study sought to investigate the impact of asymmetric temporal resolution on binaural fusion in NH listeners using a subjective rating scale, as well as validate a method for objective assessment of binaural fusion using an electrophysiologic measure of auditory change detection, known as the acoustic change complex. The ACC is thought to reflect cortical neural processing underlying auditory discrimination ability (He et al., 2012), and can be elicited by a variety of stimulus manipulations, including changes to frequency (e.g., Dimitrijevic et al., 2008), intensity (e.g., Harris, Mills, & Dubno, 2007), and interaural correlation (e.g., Chait et al., 2005; Jones et al., 1991). Further, ACC amplitude has been shown to increase with increasing magnitude of the acoustic change (e.g., Chait et al., 2005; Dimitrijevic et al., 2008; Han & Dimitrijevic, 2015; Harris et al., 2007), and has been correlated with behavioral discrimination for a number of parameters (e.g., Chait et al., 2005; Han & Dimitrijevic, 2015; He et al., 2012). Previous work demonstrating the capacity for changes in IC to elicit an ACC suggests that this may be a viable option for objective assessment of binaural fusion, since fusion is closely related to the degree of IC (Sayers & Cherry, 1957; Whitmer et al., 2012). Binaural fusion can be difficult to measure behaviorally as reports of fusion are highly dependent upon the paradigm/task used (e.g, Wess et al., 2020), and the ability of the listener to understand what is meant by "fusion." Therefore, an objective measure of binaural fusion would be extremely beneficial for gauging binaural integration both experimentally and clinically.

A. *Effect of Interaural Asymmetry on Subjective Ratings of Binaural Fusion*

Chapter IV of this dissertation investigated the effect of interaural asymmetries in temporal resolution on binaural unmasking of vocoded speech in NH listeners. We found that binaural unmasking declined with decreasing DR, and asymmetric reductions in DR negatively impacted binaural unmasking more than symmetric reductions. We postulated that interaural asymmetries in temporal resolution may have negatively impacted listeners' ability to binaurally fuse masker stimuli across ears, reducing the perceptual separation of target and masker speech. Results from the behavioral fusion measure in the present study support this theory. Listeners rated the Symmetric DR condition as being significantly more fused than the Asymmetric DR condition (Figure 4). Listeners most frequently rated the Symmetric DR condition as a level 4 on the binaural fusion scale (Figure 2), which indicates the perception of a single sound that is wide or diffuse in the head. However, the second most common rating for this condition was level 5, indicating the perception of two separate sounds. While listeners were more likely to rate the Symmetric DR condition as fused compared to the Asymmetric DR condition, this indicates that they did not perceive the Symmetric DR condition as being *strongly* fused. This is also consistent with our results from Experiment 2 in Chapter IV: listeners only demonstrated 11% of unmasking in the equivalent Symmetric 50% DR condition, which was minimal compared to the other Symmetric conditions tested (e.g., 30% of unmasking for the Symmetric 71% DR condition- Chapter IV, Figure 6). These results suggest that poor temporal encoding may severely limit binaural unmasking benefit, even in the absence of interaural asymmetries.

The Correlated SSN and Uncorrelated SSN conditions were included in order to elicit responses at both extremes of the scale: a single punctate sound, and two distinct punctate sounds. It has been previously shown that NH listeners perceive perfectly correlated stimuli as a single sound (Sayers & Cherry, 1957). Hence, it is not surprising that the Correlated SSN condition (IC=1) was rated as being the most fused. It has also been demonstrated that as IC decreases, the perceived width of the sound increases, and at very low ICs listeners may perceive multiple sounds (Whitmer et al., 2012). Therefore, we expected the Uncorrelated SSN condition to be rated as the least fused, since the sounds presented to each ear were completely independent of one another (IC=0) and had no grouping information available. Perplexingly, this condition was rated as significantly more fused than either of the AM conditions. This is surprising considering that the Uncorrelated SSN condition did not have any information that would facilitate fusion of the uncorrelated noise, whereas the AM conditions had temporal envelopes that were matched in frequency and phase. This finding may be due to multiple factors. First, the Uncorrelated SSN condition did not have a distinct reference stimulus to compare to, since uncorrelated SSN was used as the reference for all conditions. In other words, in the Correlated SSN, Symmetric DR, and Asymmetric DR conditions, listeners heard 1500 ms of uncorrelated SSN followed by 1500 ms of the condition stimulus, whereas listeners were just presented with 3000 ms of the same stimulus for the Uncorrelated SSN condition. Had listeners been presented with 1500 ms of correlated SSN first, they may have been more likely to rate the Uncorrelated SSN condition as being less fused. Second, also related to the lack of reference stimulus, the sound quality for the Uncorrelated SSN condition did not change at all throughout the duration of the stimulus. This is in contrast to the AM conditions, where the stimulus changed from unmodulated SSN to AM SSN. Even though listeners were told to ignore any changes to sound quality and simply focus on the size and number of sounds, the drastic change in sound quality due to the introduction of 20 Hz amplitude modulations may have biased listeners' ratings for the Symmetric and Asymmetric conditions.

B. Effect of Interaural Asymmetry on ACC Response Magnitude

Consistent with behavioral results indicating the binaural fusion was greatest for the Correlated SSN condition, we also observed the largest ACC response for this condition. The stimuli for this condition sound like static SSN when presented monaurally, thus, an ACC elicited by this condition can be interpreted as a direct indication of binaural processing. The ability for changes in IC to evoke an ACC has been previously demonstrated (Chait et al., 2005, 2007; Dajani & Picton, 2006; Jones et al., 1991). Consistent with prior studies, the ACC was significantly larger for the change from correlated to uncorrelated SSN (ACC 1- change *to* ref) than for the change from uncorrelated to correlated SSN (e.g., Chait et al., 2007). This is in concordance with behavioral discrimination thresholds for changes to IC- listeners are more sensitive to deviations from correlated signals than deviations from uncorrelated signals (e.g., Chait et al., 2005, 2007). Despite the observed difference in perceived fusion between Symmetric and Asymmetric DR conditions based on subjective ratings, we did not observe any significant difference in AUC magnitude between these two conditions for ACC 1 or ACC 2. Results from the behavioral measure for these two conditions suggest that neither one provoked a strong perception of fusion. Therefore, it is possible that the difference in fusion between these two conditions was not salient enough to elicit differences in the neural response. Indeed, studies have shown that, although ACC responses correlate well with behavior for many discrimination tasks, the ACC is not always as sensitive as psychophysical measures (He et al., 2012). Another possible explanation is the difference in monaural acoustic change between Symmetric and Asymmetric DR conditions. In the Symmetric condition, monaural stimuli alternated between unmodulated SSN (ref) and amplitude modulated SSN at 50% DR. In the Asymmetric condition, one ear was presented AM SSN at 50% DR, but the other ear was presented AM SSN at 100% DR, which creates a larger acoustic change from unmodulated SSN than the 50% DR. It is possible that the presence of 100% DR in the right ear for the Asymmetric condition inflated the ACC magnitude. If this were the case, then differences between Symmetric and Asymmetric conditions would not purely reflect differences in binaural fusion. This possibility is supported by results from Han and Dimitrijevic (2015) who found larger ACC amplitudes for changes from white noise to AM for 100% DR than for 50% DR AM. Further support for this possibility is evidenced by our finding that the Monaural 100% Right condition elicited significantly larger AUC magnitude than the 50% Right condition for ACC 1 and ACC 2 (Figure 7). A correlation analysis between Monaural 100% Right and Asymmetric DR response magnitudes revealed a significant positive relationship for ACC 1 (one-tailed: $r=0.41$, $p<0.05$) but not ACC 2 (one-tailed: $r_s=0.25$, $p=0.14$-Figure 8).

While the ability to elicit an ACC by manipulating IC has been well established, we were not able to objectively gauge the effect of interaural asymmetry in temporal resolution on binaural fusion using the stimuli/conditions tested in this study. However, further investigation is warranted due to the limited number of conditions tested and the potential benefits of validating the ACC as a method for objectively measuring binaural fusion. In the future, it may be advantageous to measure behavioral perception of fusion prior to electrophysiologic assessment in order to ensure that chosen stimuli/conditions elicit salient differences in fusion.

VI. Summary

The present study sought to investigate the impact of asymmetric temporal resolution on binaural fusion in NH listeners using a subjective rating scale and an electrophysiologic measure of auditory change detection, known as the acoustic change complex. We hypothesized that stimuli with greater interaural similarity would be rated as more fused, and elicit larger evoked responses. We were specifically interested in the effect of asymmetric temporal resolution on binaural fusion, as we hypothesized that diminished fusion resulting from interaural asymmetries may underlie the reduced unmasking benefit observed in Chapter IV. Results from the subjective measure of fusion are consistent with our hypothesis: The Correlated SSN condition, which had an interaural correlation of 1, was rated as the most fused, and the Symmetric DR condition was rated as significantly more fused than the Asymmetric DR condition. Consistent with subjective ratings, the Correlated SSN condition evoked the largest ACC magnitude. However, the perceived difference in fusion between Symmetric and Asymmetric DR conditions was not reflected in the neural responses. This may have been due to the fact that the difference in fusion between Symmetric and Asymmetric conditions was not salient enough to elicit a significant difference in ACC magnitude.

Acknowledgements

This research was supported by NIH-NIDCD Grant No. R01DC003083 (to RYL) and NIH-NICHD Grant No. U54HD090256 (to Waisman Center), and funds provided by the University of Wisconsin-Madison Department of Communication Sciences and Disorders to Emily Burg. Portions of this work were presented at the 2021 Conference on Implantable Auditory Prostheses and 2022 Association for Research in Otolaryngology Conference. The authors would like to Veronika Mak, Shelly Godar, Talia Rawitz, and Emma Pittman for help with participant recruitment, scheduling, and data collection, as well as the individuals who participated in this study.

VII. Figures and Tables

Figure 1

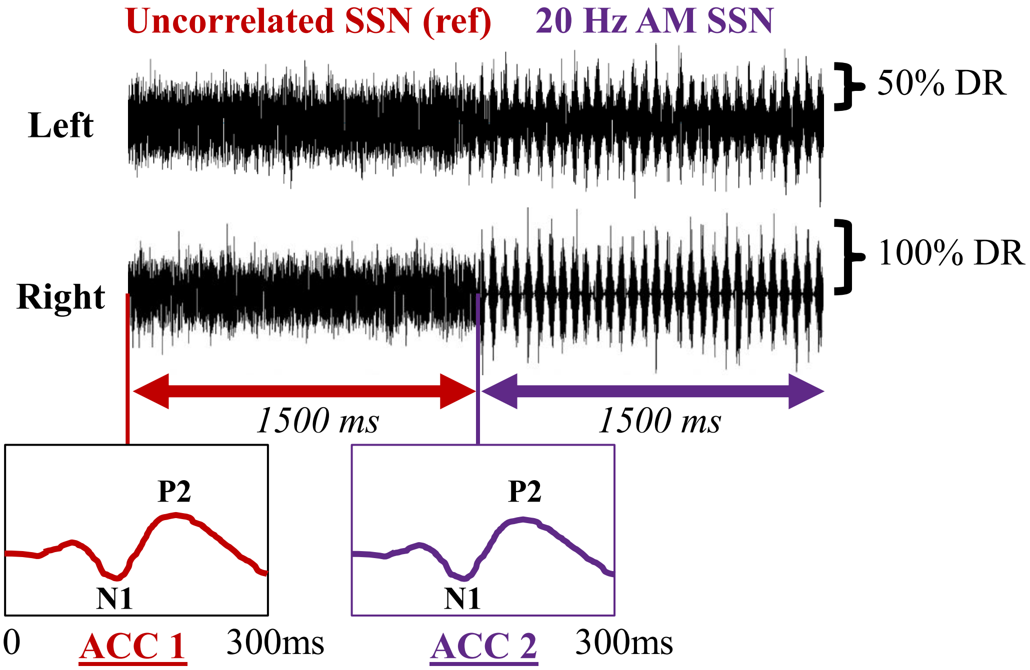


Figure 1. Illustration of binaural stimuli for one Asymmetric DR stimulus sweep, and corresponding ACCs at the change *to* the reference stimulus (ACC 1) and the change *from* the reference stimulus (ACC 2).

Table 1

Electrophysiology Conditions			
	Left Ear DR	**Right Ear DR**	**Condition Name**
Binaural	50%	50%	Symmetric DR
	50%	100%	Asymmetric DR
	Unmodulated correlated SSN		Correlated SSN
Monaural	X	100%	Monaural 100% Right
	X	50%	Monaural 50% Right
	50%	X	Monaural 50% Left

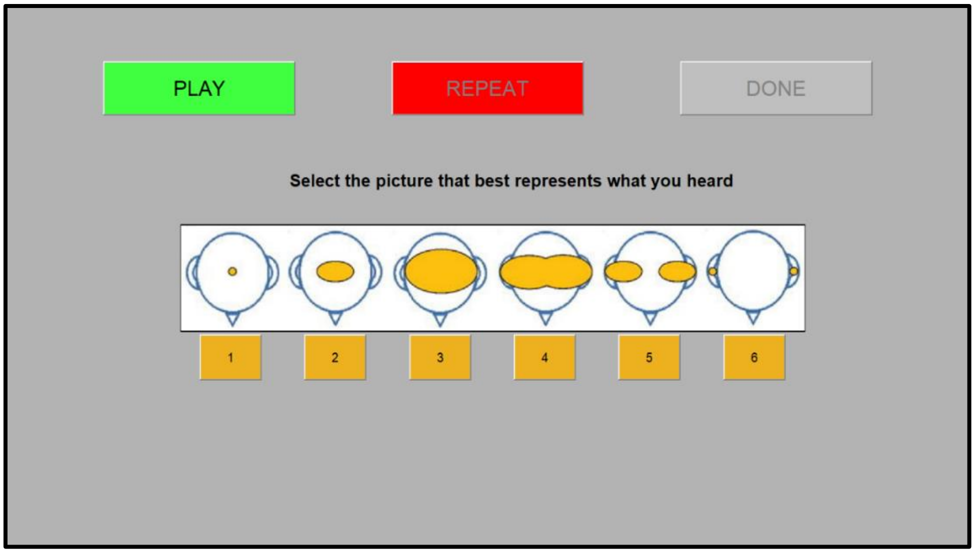
Table 1. Listening conditions tested for the electrophysiologic measure. Stimuli sweeps alternated between 1500 ms of the reference stimulus (unmodulated SSN) and 1500 ms of the condition stimulus.

Table 2

Behavioral Conditions			
	Left Ear DR	**Right Ear DR**	**Condition Name**
Binaural	50%	50%	Symmetric DR
	50%	100%	Asymmetric DR
	Unmodulated correlated SSN		Correlated SSN
	Unmodulated uncorrelated SSN		Uncorrelated SSN

Table 2. Listening conditions tested for the behavioral measure. Each trial consisted of one stimulus sweep (1500 ms reference stimulus + 1500 ms condition stimulus).

Figure 2



Select the picture that best represents what you heard

Figure 2. Participant interface for the subjective rating task. A rating of one indicates the perception of a single punctate sound, a rating of three or four indicates a single diffuse sound, and a rating of six indicates two distinct punctate sounds. 30 trials were tested per condition, and participants were allowed to repeat each stimulus as many times as needed.

Figure 3

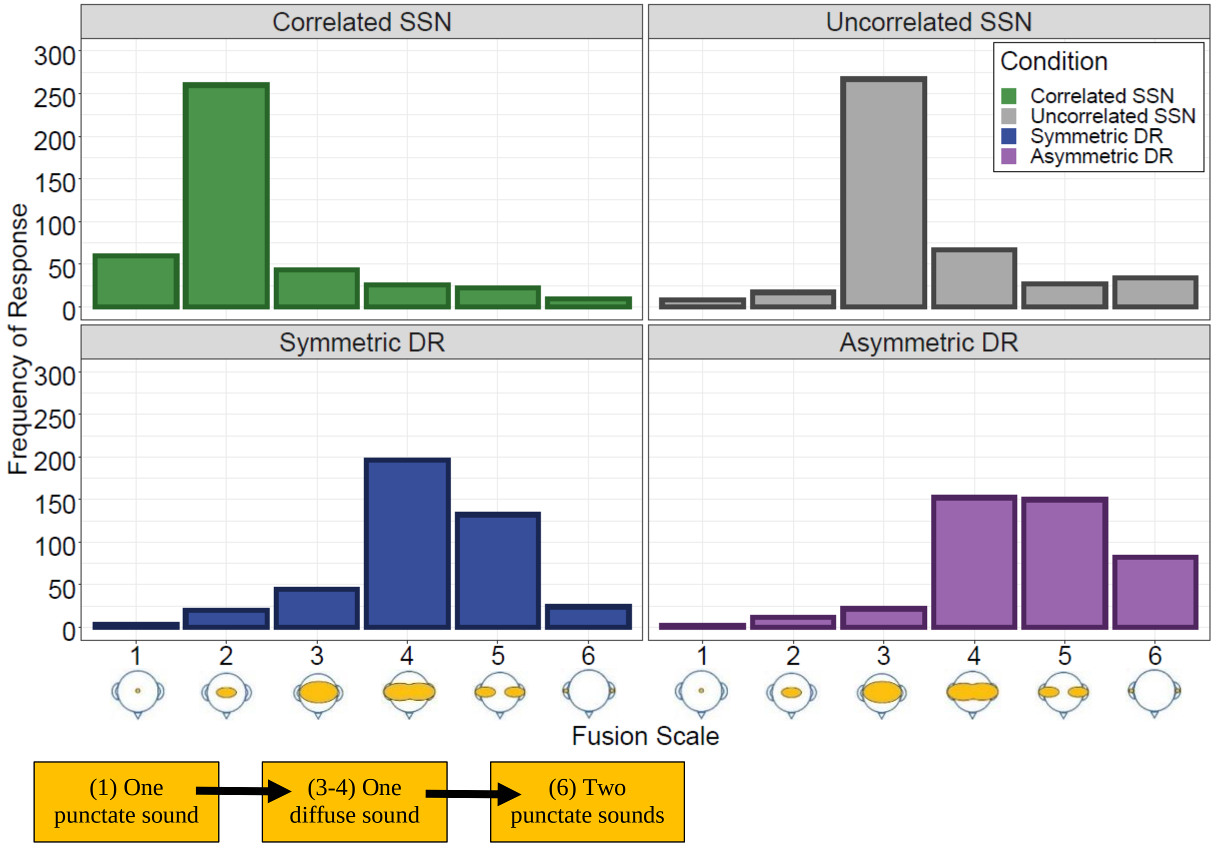


Figure 3. Histograms plotting the number of times each rating was selected for the four conditions tested in the behavioral measure (n=14). A rating of one indicates the perception of a single punctate sound (complete fusion), and a rating of six represents the perception of two distinct punctate sounds, one at each ear (no fusion).

Figure 4

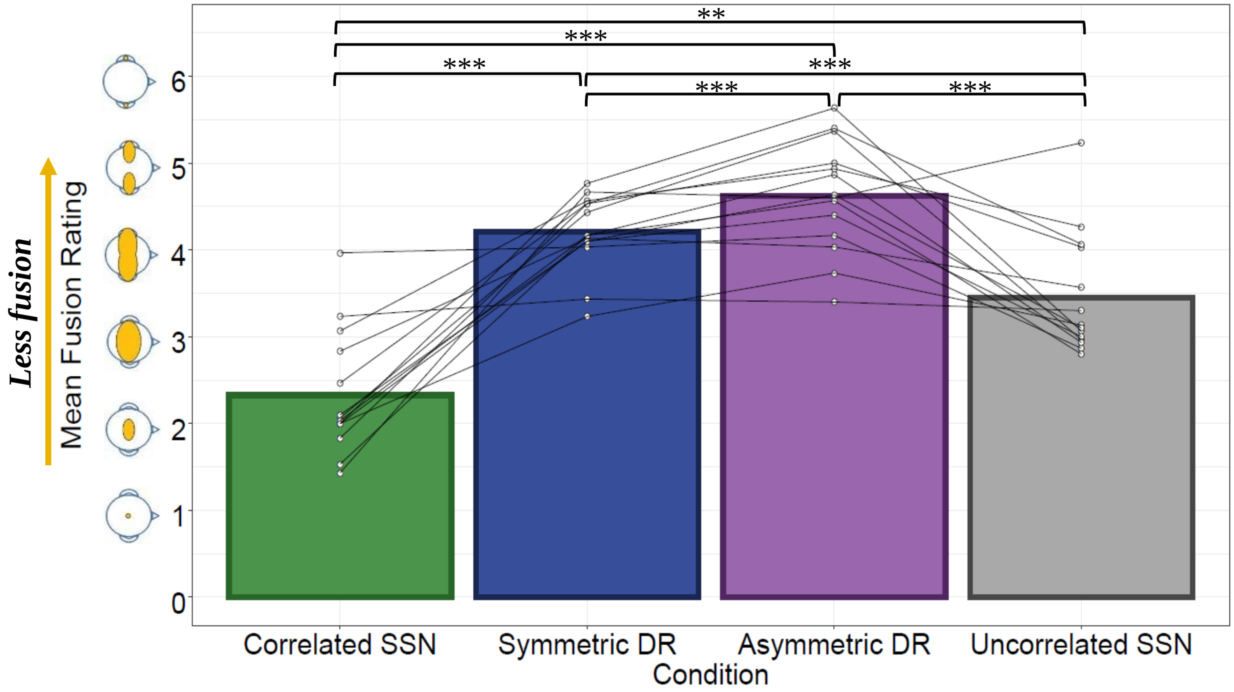


Figure 4. Mean fusion rating for the four binaural conditions tested in the behavioral measure (n=14). Error bars represent ± one standard deviation. Asterisks indicate the significance level of pairwise comparison results (* for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$).

Figure 5

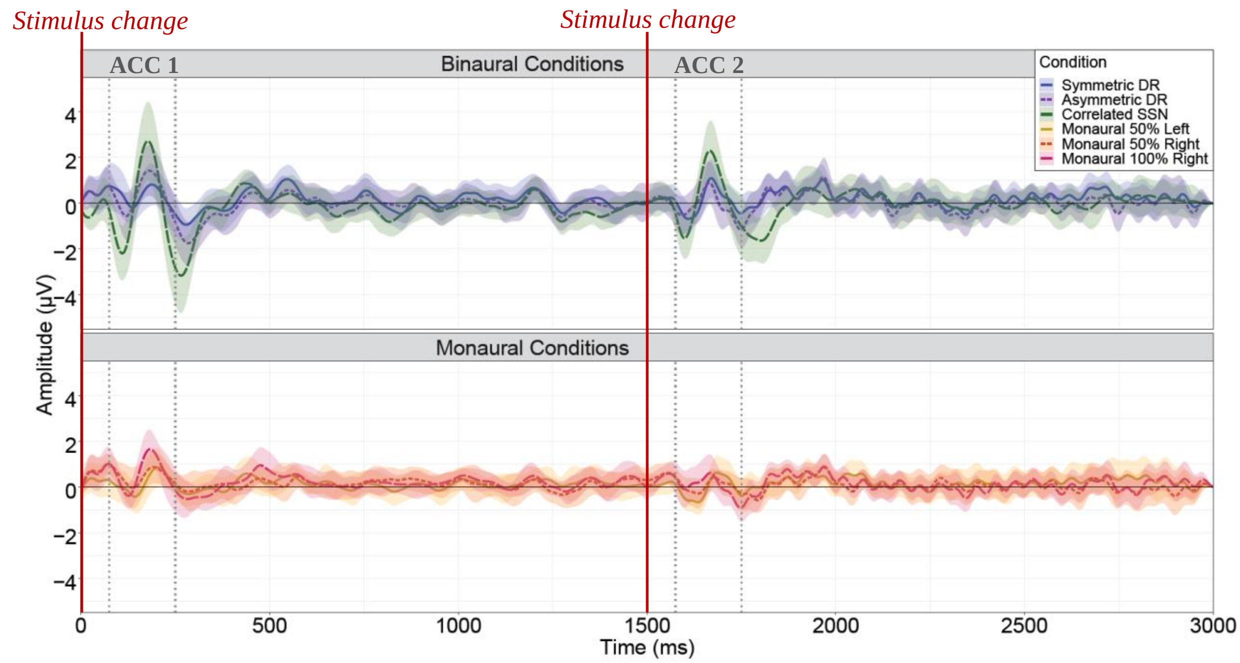


Figure 5. Grand average waveforms for binaural and monaural conditions (n=20). Standard deviation is indicated by the shaded region around each waveform. Latencies of stimulus changes used to elicit ACC responses are indicated by vertical red lines. Vertical grey dotted lines indicate the response window following the stimulus change from which the AUC metric was computed (75-250 ms post stimulus change). ACC 1 represents the change *to* the reference stimulus and ACC 2 represents the change *from* the reference stimulus.

Figure 6

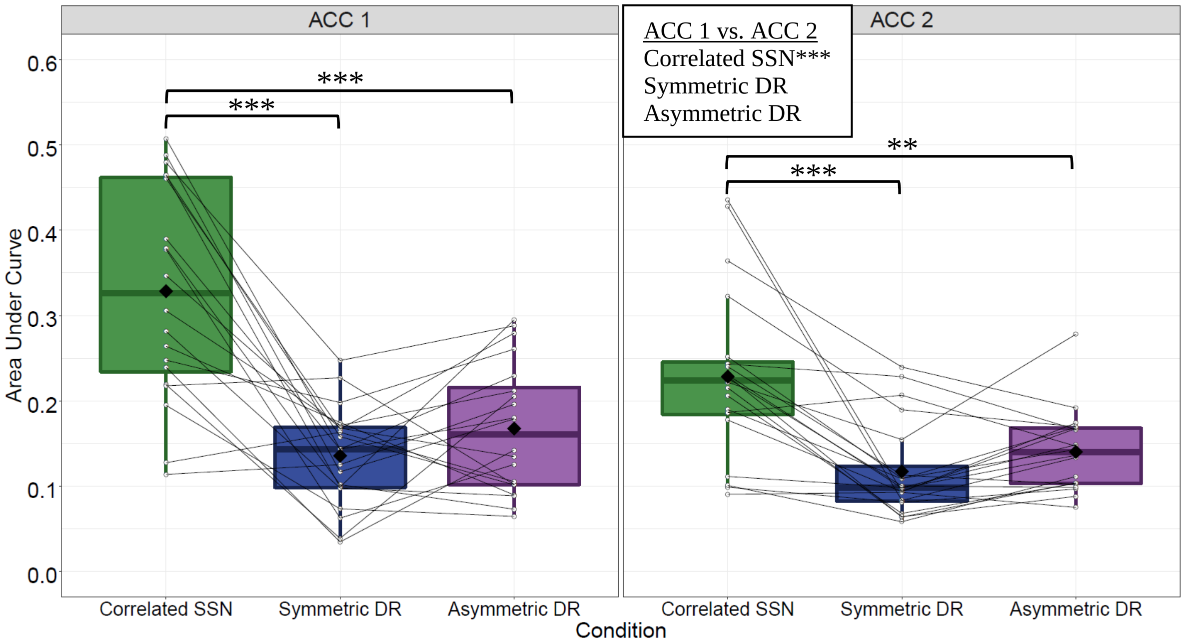


Figure 6. Area under the curve (AUC) for the change *to* the reference stimulus (ACC 1) and change *from* the reference stimulus (ACC 2) in the three binaural conditions tested in the electrophysiologic measure (n=20). Black diamonds indicate means for each condition, and small white circles represent individual participants. Group medians (MD) are represented in the box plots by a solid dark line. Asterisks indicate the significance level of pairwise comparison results (* for p < 0.05, ** for p < 0.01, and *** for p < 0.001). Significant differences between ACC 1 and ACC 2 for each condition are shown in the box labeled “ACC 1 vs. ACC 2.”

Figure 7

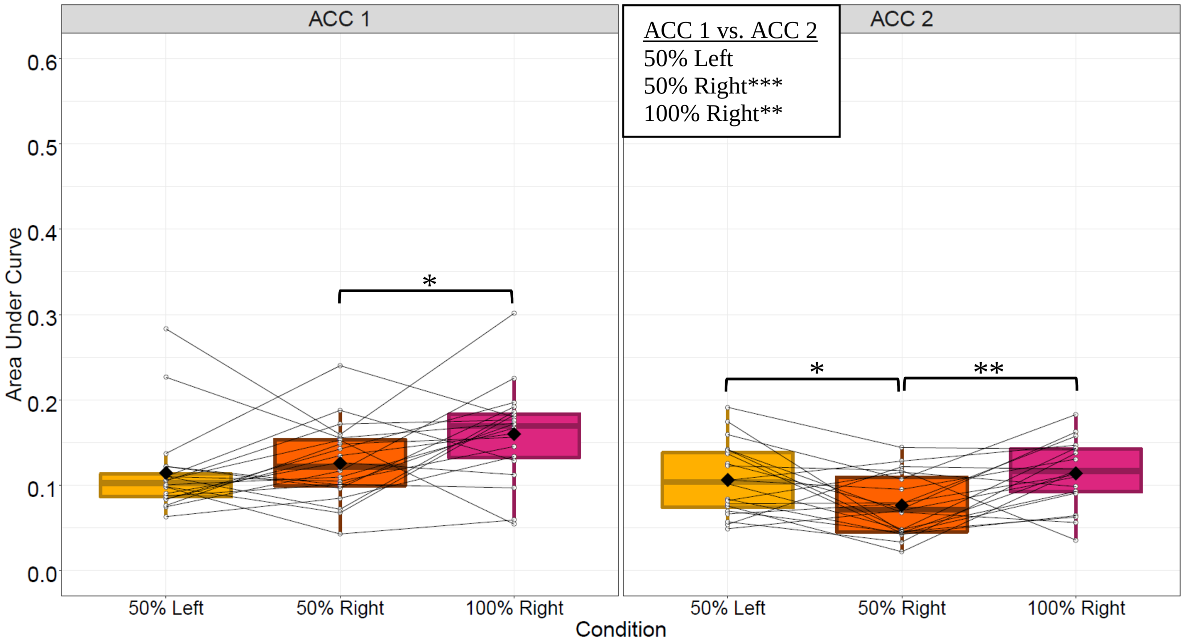


Figure 7. Area under the curve (AUC) for the change *to* the reference stimulus (ACC 1) and the change *from* the reference stimulus (ACC 2) for the three monaural conditions tested in the electrophysiologic measure (n=20). Black diamonds indicate means for each condition, and small white circles represent individual participants. Group medians (MD) are represented in the box plots by a solid dark line. Asterisks indicate the significance level of pairwise comparison results (* for p < 0.05, ** for p < 0.01, and *** for p < 0.001). Significant differences between ACC 1 and ACC 2 for each condition are shown in the box labeled “ACC 1 vs. ACC 2.”

Figure 8

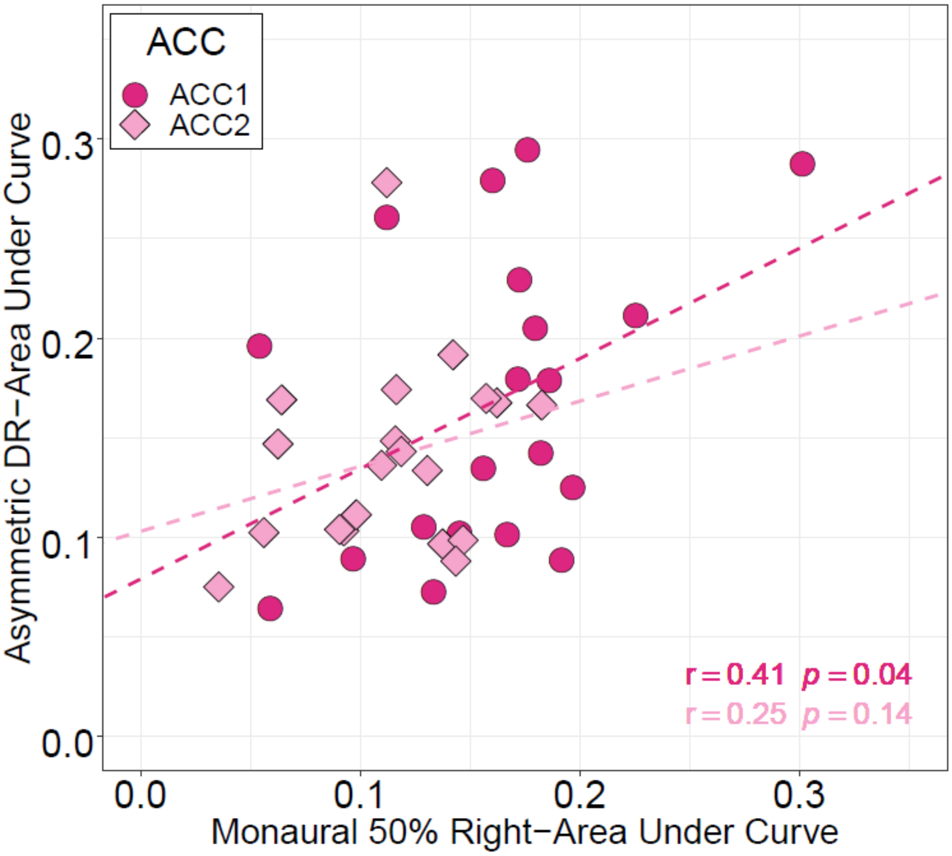


Figure 8. Scatter plot showing Asymmetric DR AUC as a function of Monaural 50% Right AUC for ACC 1 (change *to* reference) and ACC 2 (change *from* reference) with regression lines. Correlation coefficients and corresponding p-values are shown in the lower right-hand corner.

VIII. References

Akeroyd, M. A. (2006). The psychoacoustics of binaural hearing. *International Journal of Audiology*. https://doi.org/10.1080/14992020600782626

Aronoff, J. M., Shayman, C. S., Prasad, A., Suneel, D., & Stelmach, J. (2015). Unilateral spectral and temporal compression reduces binaural fusion for normal hearing listeners with cochlear implant simulations. *Hearing Research*. https://doi.org/10.1016/j.heares.2014.12.005

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society: Series B (Methodological)*. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Bernstein, J. G. W., Goupell, M. J., Schuchman, G. I., Rivera, A. L., & Brungart, D. S. (2016). Having two ears facilitates the perceptual separation of concurrent talkers for bilateral and single-sided deaf cochlear implantees. *Ear and Hearing*, *37*(3), 289–302. https://doi.org/10.1097/AUD.0000000000000284

Bernstein, J. G. W., Iyer, N., & Brungart, D. S. (2015). Release from informational masking in a monaural competing-speech task with vocoded copies of the maskers presented contralaterally. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4906167

Bernstein, J. G. W., Stakhovskaya, O. A., Jensen, K. K., & Goupell, M. J. (2020). Acoustic Hearing Can Interfere with Single-Sided Deafness Cochlear-Implant Speech Perception. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000805

Blauert, J., & Lindemann, W. (1986). Spatial mapping of intracranial auditory events for various degrees of interaural coherence. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.393471

Chait, M., Poeppel, D., De Cheveigné, A., & Simon, J. Z. (2005). Human auditory cortical processing of changes in interaural correlation. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.1266-05.2005

Chait, M., Poeppel, D., & Simon, J. Z. (2007). Stimulus context affects auditory cortical responses to changes in interaural correlation. *Journal of Neurophysiology*. https://doi.org/10.1152/jn.00359.2007

Dajani, H. R., & Picton, T. W. (2006). Human auditory steady-state responses to changes in interaural correlation. *Hearing Research*. https://doi.org/10.1016/j.heares.2006.06.003

Dimitrijevic, A., Michalewski, H. J., Zeng, F. G., Pratt, H., & Starr, A. (2008). Frequency changes in a continuous tone: Auditory cortical potentials. *Clinical Neurophysiology*. https://doi.org/10.1016/j.clinph.2008.06.002

Firszt, J. B., Holden, L. K., Skinner, M. W., Tobey, E. A., Peterson, A., Gaggl, W., … Wackym, P. A. (2004). Recognition of speech presented at soft to loud levels by adult cochlear implant recipients of three cochlear implant systems. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000134552.22205.EE

Fitzgerald, M. B., Kan, A., & Goupell, M. J. (2015). Bilateral Loudness Balancing and Distorted Spatial Perception in Recipients of Bilateral Cochlear Implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000174

Francart, T., Wiebe, K., & Wesarg, T. (2018). Interaural Time Difference Perception with a Cochlear Implant and a Normal Ear. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-018-00697-w

Gantz, B. J., Tyler, R. S., Rubinstein, J. T., Wolaver, A., Lowder, M., Abbas, P., … Preece, J. P. (2002). Binaural cochlear implants placed during the same operation. *Otology and Neurotology*. https://doi.org/10.1097/00129492-200203000-00012

Goupell, M. J., Kan, A., & Litovsky, R. Y. (2016). Spatial attention in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*, *140*(3), 1652–1662. https://doi.org/10.1121/1.4962378

Goupell, M. J., & Litovsky, R. Y. (2015). Sensitivity to interaural envelope correlation changes in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4904491

Goupell, M. J., Stakhovskaya, O. A., & Bernstein, J. G. W. (2018). Contralateral Interference Caused by Binaurally Presented Competing Speech in Adult Bilateral Cochlear-Implant Users. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000470

Goupell, M. J., Stoelb, C., Kan, A., & Litovsky, R. Y. (2013). Effect of mismatched place-of-stimulation on the salience of binaural cues in conditions that simulate bilateral cochlear-implant listening. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4792936

Grantham, D. W., Ashmead, D. H., Ricketts, T. A., Labadie, R. F., & Haynes, D. S. (2007). Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31806dc21a

Han, J. H., & Dimitrijevic, A. (2015). Acoustic change responses to amplitude modulation: A method to quantify cortical temporal processing and hemispheric asymmetry. *Frontiers in Neuroscience*. https://doi.org/10.3389/fnins.2015.00038

Harris, K. C., Mills, J. H., & Dubno, J. R. (2007). Electrophysiologic correlates of intensity discrimination in cortical evoked potentials of younger and older adults. *Hearing Research*. https://doi.org/10.1016/j.heares.2007.01.021

Harris, K. C., Mills, J. H., He, N. J., & Dubno, J. R. (2008). Age-related differences in sensitivity to small changes in frequency assessed with cortical evoked potentials. *Hearing Research*. https://doi.org/10.1016/j.heares.2008.05.005

Hawley, M. L., Litovsky, R. Y., & Colburn, H. S. (1999). Speech intelligibility and localization in a multi-source environment. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.424670

Hawley, M. L., Litovsky, R. Y., & Culling, J. F. (2004). The benefit of binaural hearing in a cocktail party: Effect of location and type of interferer. *The Journal of the Acoustical Society of America*, *115*(2), 833–843. https://doi.org/10.1121/1.1639908

He, S., Grose, J. H., & Buchman, C. A. (2012). Auditory discrimination: The relationship between psychophysical and electrophysiological measures. *International Journal of Audiology*. https://doi.org/10.3109/14992027.2012.699198

Jones, S. J., Pitman, J. R., & Halliday, A. M. (1991). Scalp potentials following sudden coherence and discoherence of binaural noise and change in the inter-aural time difference: a specific binaural evoked potential or a “mismatch” response? *Electroencephalography and Clinical Neurophysiology/ Evoked Potentials*. https://doi.org/10.1016/0168-5597(91)90152-N

Kan, A., Stoelb, C., Litovsky, R. Y., & Goupell, M. J. (2013). Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4820889

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., & Yu, G. (2004). Bilateral Cochlear Implants in Adults and Children. *Archives of Otolaryngology - Head and Neck Surgery*, *130*(5), 648–655. https://doi.org/10.1001/archotol.130.5.648

Litovsky, R. Y., Parkinson, A., Arcaroli, J., & Sammeth, C. (2006). Simultaneous Bilateral Cochlear Implantation in Adults. *Ear and Hearing*, *27*(6), 714–731. https://doi.org/10.1097/01.aud.0000246816.50820.42.Simultaneous

Loizou, P. C. (1999). Introduction to cochlear implants. *IEEE Engineering in Medicine and Biology Magazine*. https://doi.org/10.1109/51.740962

Loizou, P. C., Dorman, M. F., & Fitzke, J. (2000). The effect of reduced dynamic range on speech understanding: Implications for patients with cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/00003446-200002000-00006

Loizou, P. C., Hu, Y., Litovsky, R. Y., Yu, G., Peters, R., Lake, J., & Roland, P. (2009). Speech recognition by bilateral cochlear implant users in a cocktail-party setting. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3036175

Long, C. J., Carlyon, R. P., Litovsky, R. Y., & Downs, D. H. (2006). Binaural unmasking with bilateral cochlear implants. *JARO - Journal of the Association for Research in Otolaryngology*. https://doi.org/10.1007/s10162-006-0049-4

Lu, T., Litovsky, R. Y., & Zeng, F.-G. (2010). Binaural masking level differences in actual and simulated bilateral cochlear implant listeners. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.3290994

Martin, B. A. (2007). Can the acoustic change complex be recorded in an individual with a cochlear implant? Separating neural responses from cochlear implant artifact. *Journal of the American Academy of Audiology*. https://doi.org/10.3766/jaaa.18.2.5

Martin, B. A., & Boothroyd, A. (1999). Cortical, auditory, event-related potentials in response to periodic and aperiodic stimuli with the same spectral envelope. *Ear and Hearing*. https://doi.org/10.1097/00003446-199902000-00004

Martin, B. A., & Boothroyd, A. (2000). Cortical, auditory, evoked potentials in response to changes of spectrum and amplitude. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.428556

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology*. https://doi.org/10.1146/annurev.ps.42.020191.001031

Mills, A. W. (1958). On the Minimum Audible Angle. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1909553

Moore, D. R. (1991). Anatomy and physiology of binaural hearing. *International Journal of Audiology*. https://doi.org/10.3109/00206099109072878

Niemczak, C. E., & Vander Werff, K. R. (2019). Informational Masking Effects on Neural Encoding of Stimulus Onset and Acoustic Change. *Ear and Hearing*. https://doi.org/10.1097/AUD.0000000000000604

Ostroff, J. M., Martin, B. A., & Boothroyd, A. (1998). Cortical evoked response to acoustic change within a syllable. *Ear and Hearing*. https://doi.org/10.1097/00003446-199808000-00004

Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, S. A., Johnson, R., … Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology*. https://doi.org/10.1017/S0048577200000305

Ricketts, T. A., & Kan, A. (2021). Binaural Hearing with Devices. In R. Y. Litovsky, M. J.

Goupell, R. R. Fay, & A. N. Popper (Eds.), *Binaural Hearing* (pp. 385–417).

Ross, B., Fujioka, T., Tremblay, K. L., & Picton, T. W. (2007). Aging in binaural hearing begins in mid-life: Evidence from cortical auditory-evoked responses to changes in interaural phase. *Journal of Neuroscience*. https://doi.org/10.1523/JNEUROSCI.1813-07.2007

Sayers, B. M., & Cherry, E. C. (1957). Mechanism of Binaural Fusion in the Hearing of Speech. *Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1914990

Schleich, P., Nopp, P., & D'Haese, P. (2004). Head shadow, squelch, and summation effects in bilateral users of the MED-EL COMBI 40/40+ cochlear implant. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000130792.43315.97

Suneel, D., Staisloff, H., Shayman, C. S., Stelmach, J., & Aronoff, J. M. (2017). Localization performance correlates with binaural fusion for interaurally mismatched vocoded speech. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.5001903

Tremblay, K. L., Friesen, L., Martin, B. A., & Wright, R. (2003). Test-retest reliability of cortical evoked potentials using naturally produced speech sounds. *Ear and Hearing*. https://doi.org/10.1097/01.AUD.0000069229.84883.03

Tyler, R. S., Dunn, C. C., Witt, S. A., & Noble, W. G. (2007). Speech perception and localization with adults with bilateral sequential cochlear implants. *Ear and Hearing*. https://doi.org/10.1097/AUD.0b013e31803153e2

van de Par, S., & Kohlrausch, A. (1997). A new approach to comparing binaural masking level differences at low and high frequencies. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.418151

van Hoesel, R., Böhm, M., Pesch, J., Vandali, A., Battmer, R. D., & Lenarz, T. (2008). Binaural speech unmasking and localization in noise with bilateral cochlear implants using envelope and fine-timing based strategies. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.2875229

van Hoesel, R., Ramsden, R., & O'Driscoll, M. (2002). Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. *Ear and Hearing*. https://doi.org/10.1097/00003446-200204000-00006

van Hoesel, R., & Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.1539520

Wess, J. M., Brungart, D. S., & Bernstein, J. G. W. (2017). The effect of interaural mismatches on contralateral unmasking with single-sided vocoders. *Ear and Hearing, 38*(3), 374–386. https://doi.org/10.1097/AUD.0000000000000374

Wess, J. M., Spencer, N. J., & Bernstein, J. G. W. (2020). Counting or discriminating the number of voices to assess binaural fusion with single-sided vocoders. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/10.0000511

Whitmer, W. M., Seeber, B. U., & Akeroyd, M. A. (2012). Apparent auditory source width insensitivity in older hearing-impaired individuals. *The Journal of the Acoustical Society of America*. https://doi.org/10.1121/1.4728200

Wilson, B. S. (2019). The Remarkable Cochlear Implant and Possibilities for the Next Large Step Forward. *Acoustics Today*. https://doi.org/10.1121/at.2019.15.1.55

Wilson, B. S., & Dorman, M. F. (2007). The surprising performance of present-day cochlear implants. *IEEE Transactions on Biomedical Engineering*. https://doi.org/10.1109/TBME.2007.893505

CHAPTER VI. Summary and Conclusions

CIs are remarkable auditory prostheses that have been extremely successful in restoring speech perception abilities to patients with unilateral or bilateral severe-to-profound sensorineural hearing loss who cannot benefit from hearing aids. Compared to a unilateral CI, bilateral implants improve sound localization ability and speech understanding in noise for many patients. The majority of outcomes for individuals with SSD who receive a CI in their deaf ear are also positive, with many patients demonstrating improved spatial hearing abilities, and importantly, tinnitus suppression, which can dramatically improve patients' quality of life. However, CIs are not yet able to restore spatial hearing abilities to NH levels, and many patients still struggle to communicate in complex acoustic environments, which are common in daily life. This dissertation explored the implications of interaural asymmetries on binaural hearing outcomes in adults with SSD pre-CI and adults with BiCIs in an attempt to elucidate mechanisms that may contribute to the performance gap between NH listeners and CI users.

Chapter II aimed to investigate speech intelligibility and listening effort in adults with SSD, and validate data analysis methods for an objective measure of listening effort known as pupillometry. Results indicated that speech intelligibility was better, and maximum pupil dilation was smaller, in quiet listening conditions compared to noisy conditions in individuals with SSD and with NH. A systematic analysis of blink exclusion criteria showed that varying criterion stringency did not change the effects observed across quiet and speech masker conditions for speech intelligibility or maximum pupil dilation for either group. Nonetheless, we did find a significantly higher percentage of blinks in the masker condition relative to the quiet condition for the SSD group, suggesting that blink criterion stringency should be carefully considered in studies using pupillometry to measure listening effort.

Chapter III measured speech intelligibility and listening effort in adults with BiCIs in order to examine the potential benefits of bilateral listening in both performance and effort domains. Additionally, we were interested in the relationship between asymmetries in speech intelligibility across the two ears and bilateral outcomes. Previous studies have shown that some BiCI users can benefit from binaural redundancy, and demonstrate an increase in performance from better ear to bilateral listening. However, BiCI users tested in this study performed similarly when listening with their better CI only and with both CIs together. Additionally, listeners exhibited a significant increase in pupil dilation for bilateral compared to better ear listening. Due to the great deal of inter-subject variability, we proposed that this increase in pupil dilation likely reflected unique processes for individual participants. Six BiCI listeners demonstrated significant interaural asymmetries in speech intelligibility, and six did not. Within groups, there were no significant differences in speech intelligibility between Better Ear and Bilateral conditions, and there were no significant differences in pupil dilation between Poorer Ear, Better Ear, and Bilateral conditions. Thus, we concluded that degree of interaural asymmetry may not be sufficient to predict changes to listening effort from better ear to bilateral listening in BiCI users.

Chapter IV investigated the effect of asymmetric temporal resolution on binaural unmasking of speech in NH individuals using BiCI simulations. Stimulus dynamic range of vocoded speech was reduced symmetrically and asymmetrically across ears to investigate the effects of poor and asymmetric temporal envelope encoding in BiCI users, respectively. Speech intelligibility declined with decreasing dynamic range in both quiet and masker conditions. Further, binaural unmasking declined with decreasing dynamic range, and unmasking was greater for symmetric conditions than asymmetric conditions. Finally, we found that interaural correlation of masker noise carriers significantly affected results: binaural unmasking was greater for anti-correlated noise carriers than for uncorrelated noise carriers. These results suggest that good temporal envelope encoding is important for speech intelligibility in CI listeners, and indicate that both poor and asymmetric temporal resolution may contribute to the limited binaural unmasking benefit demonstrated by many BiCI users.

Chapter V sought to investigate the impact of asymmetric temporal resolution on binaural fusion in NH listeners using a subjective rating scale and an electrophysiologic measure of auditory change detection, known as the acoustic change complex. We hypothesized that stimuli with greater interaural similarity would be rated as more fused, and elicit larger evoked responses. We were specifically interested in the effect of asymmetric temporal resolution on binaural fusion, as we hypothesized that diminished fusion resulting from interaural asymmetries may underlie the reduced binaural unmasking benefit observed in Chapter IV. Results from the subjective measure of fusion were consistent with our hypothesis: The Correlated SSN condition, which had an interaural correlation of 1, was rated as the most fused, and the Symmetric DR condition was rated as significantly more fused than the Asymmetric DR condition. Consistent with subjective ratings, the Correlated SSN condition evoked the largest ACC magnitude. However, the perceived difference in fusion between Symmetric and Asymmetric DR conditions was not reflected in the neural responses. This may have been due to the fact that the difference in fusion between Symmetric and Asymmetric conditions was not salient enough to elicit a significant difference in ACC magnitude.

In summary, results of this dissertation demonstrate that: (1) SSD, the most extreme form of asymmetry, significantly impacts speech intelligibility in noise when the speech and noise are co-located. (2) Bilateral listening can improve speech intelligibility in quiet for some BiCI users, but there is substantial inter-subject variability. Due to this heterogeneity, the impact of bilateral listening on effort likely reflects unique processes for different individuals. For some patients, increased effort may reflect the poorer ear negatively interfering with better ear listening. For others, increased effort may be reflective of increased engagement when listening with both ears. (3) Both poor performance and asymmetry across ears have the potential to impact binaural unmasking benefit in BiCI users, but interaural asymmetry may negatively impact binaural processing more than poor performance. (4) Reduced binaural unmasking in individuals with interaural asymmetries may be due to impaired binaural fusion, which can negatively impact listeners ability to perceptually separate target and masking sounds.

With regard to clinical relevance, this works suggests that interaural asymmetry may be a significant limiting factor for binaural hearing outcomes in BiCI patients. BiCI patients who have two poor performing ears, and BiCI patients who demonstrate asymmetry across ears, may be less able to access binaural hearing benefits than other patients. Additionally, BiCI patients who are poor performers *and* demonstrate asymmetry may have an even larger binaural disadvantage, and may be at increased risk of experiencing interference in binaural tasks (i.e., worse performance with two ears vs. one). Surgical techniques and clinical interventions aimed at reducing interaural asymmetry could be very beneficial. For example, a surgical technique that could ensure equal insertion depth in each ear would reduce place-of-stimulation mismatch. Clinically, MRI scans to identify the degree of asymmetry in electrode array insertion could enable clinicians to re-allocate the frequency table of each processor to match place-of-stimulation. Additionally, loudness balancing for individual pairs of place-matched electrodes could further reduce asymmetry compared to general loudness balancing with all electrodes active.