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Clinical Implications of Binaural Interference: A Systematic Review of the Literature

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by

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Abstract

Clinical implications of binaural interference: A systematic review of the literature

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A binaural advantage has been described in many studies over the past fifty years, although research also has demonstrated examples of a disadvantage known as binaural interference. The literature varies greatly in suggesting the incidence of binaural interference across all populations. It also raises questions about the underlying causes of this phenomenon, as well as whether age-related changes have an impact.

A systematic review was engaged to summarize the literature associated with binaural interference, to identify clinical implications of this body of literature, and to answer two research questions:

1) Does the literature describe changes in susceptibility to binaural interference with age?

and

2) Does evidence suggest whether binaural interference is a central or a peripheral mechanism?

The Cumulative Index to Nursing and Allied Health Literature (CINAHL), Education Resources Information Center (ERIC), Health Source: Nursing/Academic Edition, MEDLINE and PsycINFO databases were searched, and the identified articles and reference lists were

scrutinized to identify a total of 18 articles relevant to this review. With respect to the aforementioned research questions, the literature does not help to clearly determine whether binaural interference is a by-product of aging; however, the identified studies suggest increasing evidence of binaural interference as a central mechanism. The literature described in this systematic review helps to further illustrate clinical implications of binaural interference, including behavioral and electrophysiological assessment measures, as well as rehabilitative techniques. Additionally, the reviewed studies reveal many avenues for future research.

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Introduction

The praying mantis is the only known member of the animal kingdom to have a single hearing organ; it is sometimes known as the "auditory cyclops" as a result of this atypical anatomy (Yager & Hoy, 1986). Nature has made the presence of two widely separated ears the typical, normal condition across other organisms which have an auditory system. While not all animals utilize hearing in the same way and for the same purposes, there is an assumed advantage to the placement and number of these functional organs. In the case of humans, this binaural advantage has been well documented.

Binaural Advantage

A wealth of evidence exists to support a binaural advantage, the measured benefit when listening with two ears as compared to performance of the best monaural condition, in the unimpaired auditory system (Fletcher & Munson, 1933; MacKeith & Coles, 1971; Cox, DeChicchis & Wark, 1981). A number of different advantages have been identified when listening occurs through both ears. Binaural summation of up to 10dB (Reynolds and Stevens, 1960) has been measured when listening through two ears, as has enhanced localization ability in the horizontal, vertical, and anterior-posterior planes (Musicant & Butler, 1985). Horizontal localization is improved because of the role of both interaural time and phase differences, as important directional cues are provided when the nearer ear receives the sound before the contralateral ear. Head shadow assists localization by providing an interaural difference in intensity, with the nearer ear perceiving a more intense signal. Time differences are known to be dominant for low-frequency signals, while high frequency sounds result in greater intensity differences (Zurek 1993). The pinna provides anterior-posterior and vertical localization benefits as well, due to its unique anatomical structure (Dillon, 2001).

Hearing with two ears has been shown to provide an advantage when listening to speech stimuli. A study by Chappell, Kavanagh, and Zerlin (1963) demonstrated word recognition scores that averaged 20 % greater in the binaural compared to monaural condition, using CID W-22 word lists in young adults, while Yonovitz, Dickenson, Miller, and Spydell (1979) reported comparable results in children using the Word Intelligibility by Picture Identification (WIPI) Test. Binaural redundancy and fusion have been explained as contributing factors to this phenomenon, as have binaural squelch (the combination of differing signals) and head diffraction, in which the person may attend to the ear listening on the more acoustically-favorable side. Characteristics of the signal can dictate improvements in signal-to-noise ratio (SNR); that is, as auditory signals are combined centrally, there is an attempt to suppress noise, otherwise known as the binaural masking level difference (Durlach, 1963). Ross (2006) described those aspects of binaural advantage, plus reduced communication effort when hearing through both ears. Cherry (1953) described the binaural advantage of listening in noise, also known as the "cocktail party effect." And lastly, one can consider that using two ears provides a binaural advantage because of the contrast that can be demonstrated by the effects of auditory deprivation (Silverman & Clopton, 1977; Silman, Gelfand & Silverman, 1984), that deleterious phenomenon which can occur when limiting input to one ear. In real world conditions, binaural advantage can, of course, be expected to vary from the results described in many of these studies. Although not each individual has the same habits, listening environments, abilities and communicative needs, the ultimate outcomes of listening with two ears will vary considerably by the primary signal(s), competing signal(s), environmental acoustics, as well as other factors. Several decades of studies appear to suggest that most individuals who present with bilateral normal hearing will, in most conditions, derive benefit from listening through both ears as opposed to using only one ear.

Binaural Hearing in the Presence of Pathology

A binaural advantage has been measured in the presence of bilateral sensorineural hearing loss. Gelfand and Hochberg (1976), when studying the effects of reverberation on speech discrimination, found significantly better scores in the binaural condition of not only those with normal hearing, but those with bilateral, symmetrical cochlear hearing loss. However, a number of studies have shown reduced benefit with certain neurological disorders such as multiple sclerosis (MS). Levine, et al. (1993) described subjects with MS who scored significantly poorer than normative data on measures of interaural discrimination and interaural timing. Studies have also shown those with chronic otitis media have compromised binaural hearing ability, revealed by both behavioral (masking level difference) and auditory brainstem response (ABR) measures (Hall & Grose, 1993), and they have demonstrated slow recovery of binaural function (Hall, et. Al 1995). In studying those with auditory neuropathy/dys-synchrony (AN/AD), Zeng (2006) reported significantly better speech intelligibility scores in the binaural condition when presenting a sentence recognition materials in quiet, but this improvement was not demonstrated in noise. Gopal & Kowalski (1999) studied children at-risk for auditory processing disorders (APD) using slope analysis of the ABR. The normal hearing control group presented higher slope values, as anticipated, and the majority of the APD "at risk" children had lower slopes, but the authors identified a group of children who had poor ABR waveform morphology in response to binaural stimulation, and suggested that they may represent a subcategory of those who have an absence of binaural advantage. While perhaps beyond the scope of this paper, it should be noted that some, such as Roush & Tait (1984), have studied binaural hearing in those with language-learning disabilities, and in those with disorders of mental health, (Mohr, Helm, Pulvermuller & Rockstroh., 2001). Roush & Tait showed differences in those with language-learning disabilities compared to normal controls in behavioral, but not in electrophysiological measurements, while Mohr et al. showed no difference in binaural hearing in those with schizophrenia as compared to those without the disability.

While there is much research to support binaural advantage when listening in the unimpaired auditory system, and while there are examples to support this two-ear benefit in the presence of certain types of auditory pathology, the presence of an impaired auditory system makes less clear this benefit, and presents a challenge to the research community to better understand the many variables (such as symmetry versus asymmetry, and central versus peripheral pathology) that can limit or, even as we will soon see, reverse the benefits of binaural hearing.

Amplification: One versus two hearing aids

As a result of these noted advantages of binaural input, it has long been practice to fit hearing aids in both ears in the majority of those with bilateral hearing loss (Byrne, 1981; ASHA, 1998). Despite data supporting binaural advantages (Hawkins & Yacullo, 1984), however, Cox, Schwartz, Noe and Alexander (2011) showed that 46% of subjects fit with amplification preferred monaural to binaural fittings, and they summarized from existing literature the significant number of bilateral fittings in which one instrument is ultimately rejected as “41% in field trials and 21% in retrospective surveys”, Cox, et al (2011).

Auditory Evoked Potentials: Binaural vs. Monaural Stimulaiton

As with behavioral measurement, enhancements have been documented in the results of auditory evoked potential (AEP) responses with binaural as compared to monaural stimulation. The amplitude of auditory brainstem response (ABR) waveforms have been shown to significantly increase in the binaural condition as compared to either of the monaural stimulations – a true summing effect can be documented in these earlier latency measurements (Ainslie & Boston, 1980; Debruyne, 1984). While longer latency AEP measurements have demonstrated less evidence than for ABR, for example cortical responses have not shown evidence of this summation, the middle latency response (MLR) has shown amplitude increases of waveforms produced from binaural stimulation compared to that of monaural responses (Debruyne, 1984; Weihing & Musiek, 2008). Moller & Blegvad (1976) demonstrated significant ABR waveform amplitude increases not only in those with symmetrical hearing loss, but also in people with asymmetry. Hall and Grose (1993), as previously noted, presented data suggesting reduced binaural function, as seen on ABR, in the case of individuals with otitis media, as do Zeng (2006) and Gopal & Kowalski (1999) with AN/AD and APD, respectively.

Analogy of the Visual System

With the unimpaired visual system, binocular advantage is well documented, even as there is some uncertainty as to the amount and significance (Jones & Lee, 1981). Barrett (2011) describes two main advantages of using two eyes as: binocular summation and stereopsis, the latter of which contributes to depth perception. Barrett emphasizes that the literature provides a clear binocular advantage in "visual normals", but also notes that in "stereo-deficient" individuals, binocular advantage continues to be present, although reduced. In certain types of visual pathology, such as strabismus, cataract, astigmatism, there is evidence of reduced or absent binocular advantage (Evans, 2007). The research suggests that balanced visual input is needed for the development of stereovision (Halpern & Blake, 1988; Legge & Gu, 1989). Despite this widely described binocular advantage, however, in some cases responses to binocular input may be poorer than responses to monocular stimulation, a characteristic of interference known as binocular rivalry (Blake, Brascamp & Heeger, 2014).

Binaural Interference

Despite a wealth of evidence supporting binaural advantage, a growing body of literature over the past two decades provides examples of binaural interference, first described by Jerger, Silman, Lew and Chmiel (1993) as a phenomenon where the "response from the poorer ear actually interferes with the response from the better ear (resulting in) poorer (binaural) performance…" An earlier study (Arkebauer, Mencher & McCall, 1971) presented data which appeared to demonstrate the effects of binaural interference that was later described by Jerger, et al (1993). There is literature which studied other phenomena, but which inadvertently may have also demonstrated binaural interference, such as Feuerstein (1992). Since the earliest studies, a number of publications have attempted to further define this phenomenon as researchers try to understand the underlying mechanism associated with binaural interference across populations.

It should be noted that there is a body of literature subsequent to a publication of McFadden & Pasanen (1976), who described a phenomenon of "binaural interference" upon observing that "just-noticeable differences in interaural time difference (ITD) for a high frequency narrowband noise were elevated by the presence of a simultaneous low-frequency noise presented diotically" (Best, Gallun, Carlilie, Shinn-Cunningham, 2007). As the "binaural interference" associated with those studies does not make use of monaural and binaural performance comparisons due to its significantly different definition, for the purposes of this review, while those related publications have been read and are included in the reference list, they are excluded from the content of this paper. However, identified studies which define binaural interference as a phenomenon in which there is a decrease in performance in the binaural condition as compared to a monaural condition are analyzed and summarized.

Objectives and Research Questions

Binaural advantage has been described in many studies, and is a common phenomenon in the unimpaired auditory system. Research has also described a disadvantage known as binaural interference. The literature varies considerably, although certain similarities seem to be present. This review is designed to systematically summarize published studies to help determine the answers to two questions:

1) Does the literature describe changes in susceptibility to binaural interference with age?

and

2) Does evidence suggest whether binaural interference is a central or a peripheral mechanism?

Analysis of the literature will additionally serve to consider needs and avenues for future research on the topic, as well as clinical implications of the current knowledge base.

Methods

A comprehensive search was performed in May, 2014 using the Cumulative Index to Nursing and Allied Health Literature (CINAHL) Plus with full text, Education Resources Information Center (ERIC), Health Source: Nursing/Academic Edition, MEDLINE, and PsycINFO databases. Additionally, reference lists of each identified article were manually searched to target additional, relevant articles not found in the database search. Search terms included “binaural interference”, “binaural rivalry”, “binaural inhibition”, “bilateral interference” AND hearing, “hearing interference” and “monaural advantage”.

Inclusion of published studies in this systematic review was guided by PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses), formerly QUOROM (QUality Of Reporting Of Meta-analysis), as described by Moher D, Liberati A, Tetzlaff J, Altman DG (2009). The PRISMA Statement consists of a 27-item checklist and a four-phase flow diagram (Fig. 1), the aim of which is to help authors improve the reporting of systematic reviews and meta-analyses.

Publications related to the McFadden and Pasanen (1976) definition of “binaural interference” as “just-noticeable differences in interaural time difference (ITD) for a high frequency narrowband noise were elevated by the presence of a simultaneous low-frequency noise presented diotically” were excluded from this review for reasons mentioned previously.

The publication bias which may exist by only searching databases with published studies, and only studies in English, is acknowledged.

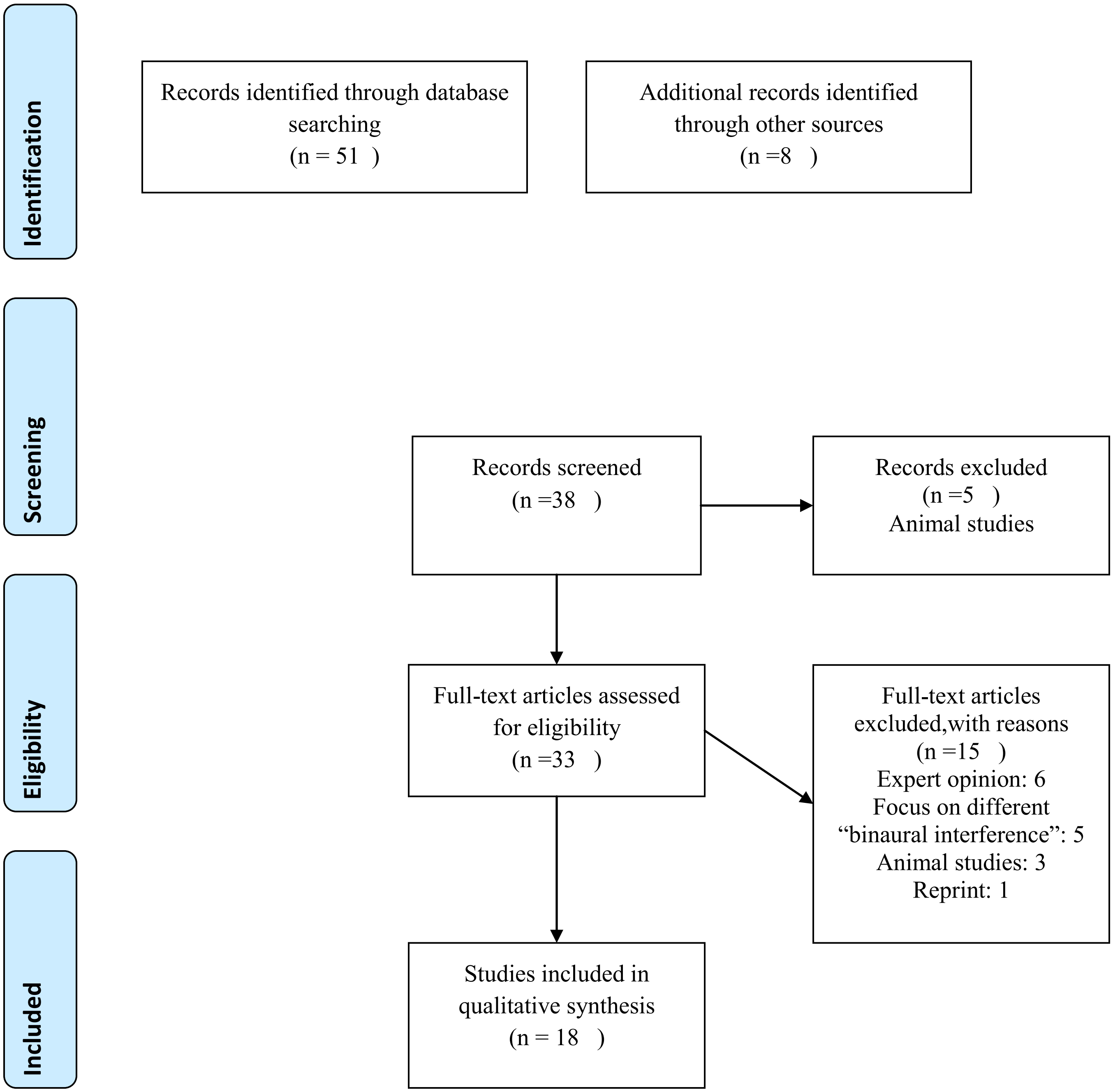

Figure 1. Flowchart of the literature search and retrieval process, as guided by PRISMA (D, Liberati A, Tetzlaff J, Altman DG, 2009)

Results

Fifty-one articles were identified for title and abstract review utilizing combinations of selected keywords in the library databases, as previously described. Eight additional articles were identified by other sources. Following removal of duplicates, thirty-eight were screened using title and abstract review, of which five were excluded as they did not involve human subjects. Full-text review of the remaining thirty-three articles revealed several articles of expert opinion, and others which included an alternative definition of "binaural interference" which is not relevant to this review; thus reducing the final list to eighteen published articles. The search and retrieval process is illustrated in Figure 1.

A summary of the studies chosen for inclusion in this review is illustrated in Table 1. The summary provides a description study design, number and age of participants, as well as additional relevant characteristics, a description of the outcome measures, and summarized results.

Research Question 1

Does the literature describe changes in susceptibility to binaural interference with age?

Of the eighteen studies included in this review, six studied children alone, nine studied adults, two were of mixed (children and adult) groups, and one was undefined. Of the adult studies, two distributed their subject pool into age groups. It should be noted that of studies which did not describe data by age groups, five contained subjects from quite heterogenous age groups, ranging fifteen years or more.

The study of binaural interference in adults

Binaural interference was first described in detail with the presentation of four cases in a paper by Jerger, Silman, Lew and Chmiel (1993), highlighting results of both behavioral and electrophysiological measurements in people with sensorineural hearing loss. In Case 1, an experienced 71 year-old female hearing aid user with moderately-severe sensorineural hearing loss was presented. Using CID W-22 words presented at 30dBSL, scores of 50% in the left ear and 0% in the right ear were measured unaided. Aided results were 64% in the left ear, 0% in the right ear and a score of 22% was obtained binaurally aided. Thus, monaural left results were significantly better than binaurally aided word recognition scores. Case 2 described results of a 66 year-old male who had reported decreased hearing in his left ear following recovery from viral encephalitis. Middle latency response (MLR) using topographic brain mapping was employed, with results showing the right ear responses to be greater than those of left monaural and that of binaural stimulation. Case 3 described an 80 year-old male with a history of stroke affecting left-brain. With similar pure tone thresholds indicating a sloping SNHL bilaterally, asymmetrical word recognition scores of 80% in the left ear and 36% were noted. Aided scores revealed results similar to Case 1: an aided left score of 76%, and aided right of 8% were obtained, while binaurally aided results were 54%, a significantly poorer score than that of the best monaural ear. MLR was additionally measured, with results showing a significantly reduced waveform amplitude of P_a in the binaurally-stimulated condition, as compared to either monaural stimulation. Lastly, Case 4 also described behavioral and electrophysiological results, this time of an 81 year-old male with gradual-onset mild SNHL, presenting with asymmetrical word recognition scored of 100% and 60% in the right and left ears, respectively. Using brain mapping, MLR results again showed poorer responses in the binaural condition as compared to monaural stimulation, although ABR results did not have this finding. An aided cued-listening task in soundfield indicated greater errors of localization in the binaurally aided condition. Jerger, et al. concluded that under certain conditions in the four cases, stimulation of the poorer ear interfered with the better ear, causing a decrease in binaural ability – a binaural interference.

Silman (1995) published a case study of a male with multiple sclerosis who exhibited binaural interference. The 36 year-old presented with a left, sudden unilateral, normal sloping to profound SNHL, and left tinnitus. ABR and MLR results showed normal waveforms in the right ear, but absent responses in both the left and binaurally-stimulated responses, demonstrating binaural interference. However, magnitude of binaural interference decreased as the gentleman progressed from the active to remission stage of the disease.

Chmiel, Jerger, Murphy, Pirozzolo, & Toole-Young (1997) observed speech-recognition performance in a binaurally-aided 90-year old female with essentially bilaterally symmetrical, sloping sensorineural hearing loss who expressed dissatisfaction with binaural amplification, particularly when in the presence of noise, since having been fit three years earlier. Chmiel et al. (1997) performed several behavioral and electrophysiological measurements on the participant, including a battery of dichotic speech tests: Dichotic Sentence ID Test (DSI), Cued Listening Test and dichotic PB words, P300 in verbal and nonverbal conditions and the synthetic sentence test in monaural vs binaural conditions. Results showed significant left ear disadvantage and binaurally aided results that were poorer than the best monaural results. In addition, a left ear disadvantage was obtained in the verbal condition and a right ear disadvantage was obtained in the non-verbal mode. The investigators hypothesized that the binaural interference reflects "difficulty with binaural amplification (that) may be explained by age-related progressive effects of the demyelinated corpus callosum causing a deficit in interhemispheric auditory transfer", taking into account the role that the corpus callosum has in processing of binaural information, and suggesting the role of age-related changes.

Although the term "binaural interference" was not used, it was described in the results of Arkebauer et al. (1973). Measurements from ten adults with bilateral asymmetrical SNHL were studied, with word recognition scores (CID W-22) poorer in the binaural condition than in the better monaural condition in 90% of subjects studied, although results from each were not significantly different. Occluding the poorer ear resulted in recognition score improvement of between 2-18%, early examples of both binaural interference and an attempt to limit the deleterious effect.

Holmes (2003) presented the case of a 69 year-old female with rising severe to moderate bilateral symmetrical SNHL, to help contribute to the body of literature which poses the question about whether two hearing aids are better than one in older populations. Using CID sentences, significantly better results were obtained in the monaurally aided right condition as compared to the aided left or binaural conditions. Despite the apparent binaural interference measured in this person, Holmes concludes by noting that arguments for bilateral amplification "far outweigh" any disadvantages, and that bilaterial amplification should be recommended unless there is a suspected contraindication. However, one must be mindful of the possibility of interference during the trial period for amplification.

Leigh-Paffenroth, Roup, and Noe (2011) studied binaural processing in those with symmetrical HL using both behavioral and electrophysiological measures. Nineteen adults, without evidence of neurological impairment, with symmetrical pure tone audiometry, asymmetrical word recognition and dissatisfaction with binaural HA fitting based upon Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire, participated in the study, The WIN paradigm (word recognition in MT babble), Dichotic Digits Test (DDT), 500Hz Masking Level Difference (MLD), and MLR were measured. Binaural measurements in both behavioral and electrophysiological tests revealed significantly decreased binaural processing in ten of the subjects. A strong correlation between MLD and MLR Na-Pa amplitude was noted.

Studies have considered the implications of binaural interference in those fit with cochlear implants. Yoon, Shin and Fu (2013) studied the the effect of binaural spectral mismatch on localization ability in speech perception using cochlear implant simulation. Six females and four males aged 21-55 with hearing within normal limits participated in the study. Sentence recognition using IEEE Sentences at +5 and +10 SNR was presented to participants via cochlear implant simulators in unilateral and bilateral listening conditions. Bilateral spectral mismatch demonstrated measurements indicating binaural interference for certain binaural characteristics, squelch and redundancy, that were measured. The authors emphasize that cochlear implant mapping should be "administrated for bilateral CI users in a manner that minimizes the difference of spectral patterns between two CIs", so as to limit the possibility of binaural interference. Ching, Psarros, Hill, Dillon & Incerti (2001) also studied binaural interference with use of cochlear implants, although the research is summarized with other child studies.

Not all studies measured significant prevalence of binaural interference in adults. Allen et al. (2000) studied the prevalence of binaural interference in young and elderly listeners with normal hearing, and elderly participants with sensorineural hearing loss. Participants were distributed into four groups as follows: : young WNL, older WNL, older HL aided, older HL unaided, with age ranges of 20-24, 65-86, 61-93, 65-89, respectively. Word recognition scores using CID W-22 measured monaural right, monaural left and binaural were obtained, with 4% of all subjects (2/48) exhibiting statistically significant binaural interference. It should be noted that 58% of subjects in the older within normal limits group performed better in monaural than binaural, even if only one of the individuals from that group did not perform at a significantly better level monaurally.

Similarly, Karsten and Turner (2000) presented data which did not reveal binaural interference. They studied the effect of altering the presentation levels of speech to the ears of people with asymmetrical SNHL. Two females and ten males with bilateral, asymmetrical hearing loss were included. Speech recognition scores were measured in monaural and binaural conditions, with no significant difference seen in monaural versus binaural in each of the various intensity conditions. One must consider the small sample of twelve participants when interpreting this data.

In contrast to studies showing no evidence of binaural interference is a study by Walden & Walden (2005), who compared outcomes of unilateral and bilateral amplification in adults with hearing loss. Participants included twenty-eight adults (26 males/2 females), aged 50-90 years old (mean of 75.1), including twenty-three experienced hearing aid users and five new users. Each participant presented with bilateral, symmetrical SNHL. Measurements included speech recognition in noise testing using QuickSIN and Dichotic Digit Test (DDT). The investigators measured significantly poorer binaural speech recognition performance on QuickSIN in a surprisingly high 82% of subjects. Additionally, the authors reported that a statistically weak relationship suggested increased susceptibility to binaural interference with age

McArdle, Killion, Mennite & Chisholm (2012) sought to replicate the conditions of Walden and Walden (2005), and to examine the use of binaural cues to improve speech perception in noise. Twenty males aged 59-85 (mean of 75.5) with bilateral symmetrical SNHL, participated; each was an experienced hearing aid user fit with new digital devices. Speech recognition using QuickSIN in different monaural and binaural conditions revealed that 20% of subjects performed better monaurally, in contrast to the Walden & Walden (2005) data. Additionally, a monaurally aided task was conducted with each subject's unaided ear plugged, so as to create a true "monaural" condition, to improve upon a perceived flaw in the Walden data. Results were expectedly limited in the monaural aided condition when the contralateral ear was plugged as compared to Walden & Walden (2005)

There are fewer studies describing binaural interference in children as compared to adults. Schoepflin (2007) presented a pediatric case study of binaural interference in which a 1.6 year-old male was fit with monaural amplification three years before meeting the author of the publication. The child presented with severe symmetrical SNHL bilaterally, and was subsequently (at the age of 4.6) evaluated and asymmetrical word recognition scores were identified. At that time it was considered that the word recognition asymmetry may have been emblematic of the effects of auditory deprivation, thus, he was fit in both ears to potentially offset or reverse the effects of deprivation. Once he was fit, however, his social and academic status worsened considerably, and he was referred to the author. At that time, word recognition scores were obtained consistent with the presence of binaural interference.

Johnstone,, Náblek, & Robertson, (2010) studied localization ability in children with unilateral hearing loss. Twelve children, aged 6-14, who wore hearing aids were matched with twelve normal controls. Each member of the experimental group of twelve presented with sensorineural hearing loss; two subgroups of five children were formed, one group with mild-moderate SNHL, and one group of moderately-severe hearing loss. The two remaining children had atypical hearing loss (cookie bite and reverse-slope). Children were asked to make location judgments on a computer in response to the word "baseball" presented from a variety of speakers. A significant interaction was identified between amplification and child age: improved localization ability was noted in the 6-9 year-old group, while children fit later (10-14 years of age) showed bilateral interference, although the authors note that development may play a role in localization ability as evidenced by the difference in unaided results between the two groups.

Gopal & Kowalski (1999) studied children at-risk for auditory processing disorders (APD) using slope analysis of the ABR. Eighteen 7-13 year olds participated in this study: nine without impairment and nine at risk of APD, each participant presenting with hearing within normal limits bilaterally. Those deemed to be "at risk" were identified using the SCAN/SCAN-A.

ABR waveform morphology was measured by slope vectors, with the normal hearing control group presenting expectedly higher slope values, and the majority of the APD "at risk" children presenting lower slopes. However, a subcategory of the "at-risk" children with poor ABR waveform morphology when binaurally stimulated was identified. Gopal & Kowalski (1999) indicate that a subgroup of children at risk for APD may have binaural interference, and that use of ABR slope analysis may serve as a tool to assist identification.

Green & Josey (2002) studied whether use of an earplug in children with learning disabilities would increase speech comprehension. This large-scale study utilized 238 child participants, aged 7-15, distributed across three groups as follows: Group 1 - Control (66 male, 66 female), Group 2: Heterogenous learning disabilities (60 male, 28 female), and Group 3: learning disability with monaural advantage (14 male, 4 female) – identified following Group 1 and 2 results. Test protocol involved the immediate recall of thirty stories in left-only, right-only, and binaural conditions. Those who exhibited monaural advantage in this activity were given an earplug and repeated. Results revealed binaural advantage measured in the control group, binaural interference measured in each of the two experimental groups, which was reversed via use of an earplug in the poorer ear. The authors indicate that the reasons for this phenomenon are not well understood, and suggests that studies of cerebral metabolism may shed light. They also wonder whether the phenomenon changes over time, and refer to cases of binaural interference in those with mental illness, such as schizophrenia, as also referenced by Mohr et al. (2001).

As with the adult studies, not all literature studying binaural interference in children has produced evidence demonstrating this phenomenon. From the world of cochlear implant literature is a study from Ching et al. (2001), who investigate whether use of a cochlear implant in one ear and a hearing aid in the other causes binaural interference. Sixteen 6-18 year-olds (6 male, 10 female) participated in the study, with all having congenital hearing impairment and a minimum six months of cochlear implant use. Speech tests (BKB/A sentences, VCV nonsense syllables), localization tests and parent observations were measured. In this study, no binaural interference was measured in any subject on speech measures, and the data collected from parent observations matched.

In a study of both adults and children, Rothpletz, Tharpe, & Grantham (2004) investigated the impact of asymmetrically degraded speech signals on speech recognition in children and adults. Forty-two participants included twenty-eight children split into a younger (comprised of seven males and seven females 5-6 years old), and older (six males and eight females) group, while fourteen adults (five males and nine females ranging from 24-29 years of age) participated. All subjects presented with hearing within normal limits, and were screened for language and learning disabilities. Measurements were made using HINT-C sentences (for both adults and children) in the presence of six-talker babble, all of which was degraded by filtering to simulate hearing loss (both mild and severe). Sentences were presented in differing signal-to-noise ratio conditions. All participants exhibited binaural advantage in the mild hearing loss simulation conditions. Overall the adults, but not children, presented data that was skewed more poorly in the binaural stimulation for the severe HL simulation (1 dB poorer for adults in the binaural-asymmetric condition). However, roughly half of the children showed binaural interference in that condition and half showed advantage (which the authors described as "binaural indifference" in children). The authors ask readers to use caution when interpreting their results, however, as "even if the simulations used in the current project were perfect, these manipulations of the speech signal cannot account for the years of experience that one would have acquired as a listener with asymmetrical hearing loss or asymmetrical speech perception ability."

<u>Research Question 2</u>

Does evidence suggest whether binaural interference is a central or a peripheral mechanism?

Arkebauer et al. (1973) reported on measurements from ten adults with bilateral asymmetrical SNHL, with word recognition scores poorer in the binaural condition than in the better monaural condition in 90% of subjects studied. He suggested from this behavioral study that the degraded signal may have resulted in what is now described as binaural interference.

Jerger, et al. (1993) and Silman (1995) provided the first electrophysiological evidence suggesting a central mechanism. Case studies in both papers presented significantly different waveform morphology and reduced activity documented from topographic brain mapping measurements in binaurally-stimulated testing as compared to results obtained from monaural stimulation.

Jerger, Alford, Lew, Rivera, & Chmiel (1995) and Chmiel et al. (1997) presented additional evidence of a central mechanism in binaural interference. Their study involved thirty-six participants distributed into five groups as follows:

1. 11 young adults (18-32yo, mean 23.6)
2. 11 older adults (73-84yo, mean 77.2) w SNHL
3. 4 (81-88yo) with dichotic deficits
4. 6 (10-56yo) with lesions of the corpus callosum
5. 4 young adults (21-32 yo) hearing WNL used to evaluate peripheral distortion effects.

Verbal and nonverbal task P300 topographic brain mapping was used to measure an increased left ear disadvantage on verbal tasks and a right ear disadvantage on nonverbal task in elderly groups, which was comparable to that of the subjects with corpus callosum lesions. Jerger et al. suggested that aging is associated with decreased corpus callosum function, a hypothesis that was again stated in presentation of the case of the 90 year-old female who rejected binaural amplification (Chmiel et al, 1997)

Leigh-Paffenroth et al (2011) further expanded on the findings of Jerger et al (1993), and Chmiel et al (1997) by investigating electrophysiological and behavioral measures in nineteen adults with bilateral, symmetric hearing sensitivity who expressed dissatisfaction with binaural amplification. Speech perception tests, MLR data and masking-level difference results were consistent with binaural interference.

Table 1. Summary of Included Publications

Authors	Purpose	N	Age	Subject Characteristic s	Description/ Outcome Measures	Results
Allen, et al. (2000)	To study prevalence of binaural interferenc e in young and elderly listeners with normal hearing, and elderly w HL	48	Four groups, age range: 20-24, 65-86, 61-93, 65-89	Four groups: young WNL, older WNL, older HL aided, older HL unaided	WRS using CID W-22; measured monaural R, monaural L and binaural. Best monaural score was compared to binaural score.	4% of all subjects (2/48) exhibited statistically signific. binaural interference (58% of subjects in the older WNL group performed better in monaural than binaural, however
Arkebauer et al. (1973)	To study the performanc e of those with asymmetric al SNHL in different listening conditions including monaural and binaural	10	unreported	Bilateral asymmetrical SNHL	Word recognition scores using W-22 in monaural right, left, soundfield (sf) unoccluded and sf poorer ear occluded	Results were poorer in the binaural condition than in the better monaural condition in 90% of subjects (although not all significantly. Occluding the poorer ear caused improvement in WRS of 2-18%
Ching et al. (2001)	To determine whether use of a CI in one ear and HA in the other causes binaural interferenc e	16	6-18 (6 male, 10 female)	Congenitally HI, minimum 6 mo CI use.	Speech tests (BKB/A sentences, VCV nonsense syllables), localization tests and parent observations	No binaural interference was measured in any subject on speech measures. Parent observations matched.
Chmiel, et al. (1997)	To further study the reasons for	1	90yo	Bilateral, sloping SNHL which is	Dichotic Sentence ID Test (DSI), Cued Listening	Results showed significant left ear disadvantage and

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
	dissatisfaction with binaural amplification in a 90 year old female			essentially symmetrical, but with asymmetrical unaided WRS, using binaural amplification for 3 years, dissatisfied	Test and dichotic PB words, P300 in verbal and nonverbal conditions, synthetic sentence test in monaural vs binaural conditions	binaurally aided results which were poorer than the best monaural results
Gopal & Kowalski (1999)	To study slope analysis of ABR in children at risk for APD	18	7-13	9 without impairment and 9 at risk of APD; all hearing WNL	ABR was conducted on experimental (at risk of APD) group and control group. APD risk was assessed by SCAN/SCAN-A. ABR waveform morphology was measured by slope vectors	The authors found a subcategory of the "at-risk" children with poor ABR waveform morphology in binaural stimulation condition
Green & Josey (2002)	To study whether use of an earplug in children with LD will increase speech comprehension	238	7-15	Group 1: Control (66 male, 66 female) Group 2: Heterogenous LD (60 make, 28 female), Group 3:LD with monaural advantage	Immediate recall of 30 stories, those who exhibited monaural advantage were given earplug and repeated.	Binaural advantage measured in control group, binaural interference was measured in the two experimental groups, and was reversed via use of earplug
Holmes (2003)	To determine whether two HAs are better than one in older populations	1	69yo female	Severe to moderate, bilateral symmetrical SNHL of unknown etiology	CID sentences	Significantly better results with aided R compared to aided L or binaural conditions
Jerger, Silman et al	To present four cases of binaural	4	66-81	Various degrees of HL bilaterally	Case 1: word recognition score Case 2: MLR with	Case 1: reduced WRS in binaural condition

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
(1993)	interference in older individuals using various measures				topographic brain mapping Case 3: WRS and MLR Case 4: Aided cued listening technique and MLR	Case 2: MLR with topographic brain mapping showed reduced response to binaural stimulation Case 3: reduced WRS aided binaurally, and reduced MLR response in binaural stimulation conditions Case 4: Aided cued listening technique and MLR with mapping revealed poorer responses in the binaural condition
Jerger et al (1995)		36	Five groups 1. 11 young adults (18-32yo, mean 23.6) 2. 11 older (73-84yo, mean 77.2) w SNHL 3. 4 (81-88yo) w dichotic deficits 4. 6 (10-56yo) w lesions of corpus	Five groups of subjects were studied: young adults w hearing WNL, older adults with bilateral symmetrical SNHL, older adults with dichotic deficits, subjects with lesions of the corpus callosum and an additional group of those with hearing	Verbal and nonverbal task P300 Topographic brain mapping	Increased left ear disadvantage on verbal task and right ear disadvantage on nonverbal task in elderly groups comparable to that of the subjects with corpus callosum lesions suggesting that aging is associated with decreased corpus callosum function

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
			callosum 5. 4 young adults (21-32 yo) hearing WNL	WNL, used to evaluate peripheral distortioneffects.		
Johnstone, et al (2010)	To study localization ability in children with unilateral HL who wear a HA	24 (12 exp and 12 control)	6-14	The experimental group of 12 presented with SNHL and divided into subgroups, 5 with mild-mod SNHL, 5 mod-severe and 2 atypical. 12 controls w hearing WNL	Children were asked to make location judgments on a computer in response to the word "baseball" presented from a variety of speakers	Significant interaction was identified between amplification and child age. Improved localization ability was noted in the 6-9 yo group and children fit later (10-14) shoed bilateral interference, although the authors note that development may play a role in cound localization ability due to unaided results.
Karsten & Turner (2000)	To study the effect of altering the presentation levels of speech to the ears of	12	39-79 (mean 61.2)	2 females 10 males with bilateral, asymmetrical HL	Speech recognition scores were measured in monaural and binaural conditions	No significant difference was seen in monaural vs binaural in each of the various intensity conditions (i.e., no binaural

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
	people with asymmetrical SNHL.					interference was measured)
Leigh-Paffenroth et al (2011)	To study binaural processing in those with symmetrical HL using both behavioral and electrophysiological measures.	19	Adults	Symmetrical pure tone audiometry, asymmetrical word recognition and dissatisfaction with binaural HA fitting based upon APHAB, without evidence of neurological impairment	WIN paradigm (word recognition in MT babble), DDT, 500Hz MLD, MLR	Reduced binaural measurements in both behavioral and electrophysiological tests. A strong correlation between MLD and MLR Na-Pa amplitude
McArdle et al. (2012)	To replicate Walden and Walden (2005) and to examine use of binaural cues to improve speech perception in noise	20 males	59-85 (mean 75.5)	Binaural symmetrical SNHL, experienced HA users fit with new digital HAs	Speech recognition using QuickSIN in different monaural and binaural conditions	20% performed better monaurally, in contrast to Walden & Walden data; also, monaural aided condition was conducted with unaided ear plugged, so as to create a true "monaural" condition, a perceived flaw in the Walden data.
Rothpletz et al. (2004)	The impact of asymmetrically degraded speech signals on speech recognition	42	28 children (Younger group of 7M/7F 5-6yo, older 6M/8F 10-11yo) and 14 adults	Hearing WNL, screened for language and learning disabilities	HINT-C sentences and six-talker babble were degraded by filtering to simulate HL (mild and severe). Sentences were presented in	All participants exhibited binaural advantage in the mild HL conditions. Overall the adults, but not children, presented data

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
	in children and adults		(5M/9F, 24-29yo)		differing SNR conditions	that was skewed more poorly in the binaural stimulation for the severe HL simulation. However, roughly half of the children showed binaural interference in that condition and half showed advantage (which the authors described as "binaural indifference" in children.
Schoepflin (2007)	To present a pediatric case of binaural interference	1	1.6-5.3 year-old male	Severe symmetrical SNHL bilaterally	Word recognition scores in monaural and binaural conditions, reported social behavior and academic status	Child was fit monaurally at an earlier age, then when asymmetrical word recog scores were identified, he was fit binaurally to potentially reverse the effects of possible deprivation. However, after the child exhibited social and academic issues, a second opinion revealed WRS consistent with binaural interference
Silman, (1995)	To present a case of	1	36yo male,	Unilateral, sloping SNHL	ABR, MLR, WRS using W-22	ABR and MLR results show

Authors	Purpose	N	Age	Subject Characteristics	Description/ Outcome Measures	Results
	binaural interference in multiple sclerosis			in HFs left ear, tinnitus diagnosed with multiple sclerosis		evidence of binaural interference during active stage of MS. MLR performed during remission also demonstrated poorer results in the binaural condition. WRS scores poorer in the binaural condition
Walden & Walden (2005)	To compare outcomes of unilateral and bilateral amplification in adults with hearing loss	28 (26 males/2 females)	50-90yo (mean 75.1)	23 experienced HA users, 5 new. Bilateral, symmetrical SNHL	Speech recognition in noise using QuickSIN, Dichotic Digit Test (DDT)	Significantly poorer binaural performance occurred in 82% of subjects on QuickSIN. A weak relatoinship suggested increased susceptibility to BI with age
Yoon et al. (2013)	To determine the effect of binaural spectral mismatch on localization ability in speech perception using CI simulation	10 (6 females/4 males)	21-55	Hearing WNL	Sentence recognition using IEEE Sentences at +5 and +10 SNR presented to CI simulators in unilateral and bilateral listening conditions	Bilateral spectral mismatch demonstrated measurements indicating binaural interference for certain binaural characteristics: squelch and redundancy

Discussion

The purpose of this systematic review is to summarize the literature associated with binaural interference, to identify clinical implications of this body of literature, and to answer two research questions: 1) Does the literature describe changes in susceptibility to binaural interference with age? and 2) Does evidence suggest whether binaural interference is a central or a peripheral mechanism?

With respect to the question regarding age, several studies on both adults and children were described. Results are variable, with a majority of papers describing the phenomenon in both adult (Jerger et al. (1993), Silman (1995), Leigh-Paffenroth (2011) and McArdle et al. (2012) to cite a few, and child (Green & Josey (2002), Schoepflin (2007), and Johnston et al. (2010) populations. Still, a smaller number of studies failed to measure binaural interference (Karsten & Turner, 2000, and Ching, 2001).

Despite the variability in results, which come from studies quite varied in subject size, design, outcome measures and participant characteristics, there is data which stands out and which may merit further investigation. Specifically, Jerger et al (1995), Allen et al (2000), Rothpletz et al (2004) and Johnston et al (2009) provide discussion with respect to the factor of aging in their studies. Jerger at al. (1995) describes results which demonstrate a left ear disadvantage on verbal tasks and right ear disadvantage on nonverbal tasks in elderly groups, a profile which is comparable to that of subjects with corpus callosum lesions, and suggests that aging may be associated with age-related atrophy of fibers of the corpus callosum, resulting in the presence of binaural interference. Allen et al. studied word recognition in younger listeners with normal hearing, and older listeners both with and without hearing loss. Although only 4%

of all subjects (n of 48 in the study) exhibited significant binaural interference, 58% of older subjects with normal hearing performed better in monaural conditions than binaurally. Rothpletz et al. (2004) compared results of younger children, older children and adults with simulated hearing loss, concluding that binaural interference was present in the adult group, but not in children. However, the authors acknowledge the limitations of interpreting results in which hearing loss was simulated. Lastly, Johnston et al. (2010) performed measures of localization in children with unilateral hearing loss who wear a hearing aid. A significant finding in the study was that improved localization ability was noted in the younger (6-9 year old) group, while binaural interference was measured in the older (10-14 year old group). However, the authors note the possible impact of development playing a role in localization ability due to the unaided results of both groups.

Thus, while there is the suggestion of a relationship between aging and binaural interference, it is inconclusive, and in need of a larger-scale study investigating people of different age groups in a variety of dichotic listening tasks and with electrophysiological measures.

The second question, whether binaural interference is a peripheral or central mechanism, appears to be closer to an answer, based upon existing literature. Several of the earlier studies, Jerger, et al. (1993) , Silman (1995) and Jerger et al. (1995) provide evidence from both behavioral and electrophysiological measurements that strongly suggest a central mechanism. Indeed, Jerger et al. (1995) suggests influence from the corpus callosum, while cortical and midbrain involvement is suggested by the results of topographic brain mapping, ABR and MLR in the original study, Jerger et al. (1993). The conclusion from that study is that peripheral involvement was not likely because the binaural results should be at least as good as the best monaural. As stated, “marked interaural imbalance in the processing of verbal materials may be the basis for the binaural interference phenomenon (Jerger, et al 1995)

Studies which show binaural interference in people with normal hearing, such as Allen (2000), would seem to exclude the likelihood of peripheral involvement alone, as someone with hearing within normal limits should not have this experience. Gopal & Kowalski (1999) used slope analysis of ABR to show how some children at risk for auditory processing disorder exhibited both binaural interference and poor ABR waveform morphology when binaurally stimulated. Lastly, Leigh-Paffenroth et al. (2011) provide a more recent example of both electrophysiological and behavioral evidence of binaural interference. As the authors state, many reports in the literature studying “binaural compromise” have involved subjects presenting with neurological impairment or learning disability. Thus, an objective of their study was to investigate subjects without any obvious neural impairment. With these participants, the authors were able to report results in which some behavioral measures correlated well with electrophysiological measures, suggesting the value of both behavioral masking-level difference and the MLR BIC Na-Pa amplitude in studying the phenomenon of binaural interference. Indeed, in a most-recent example, Weihing and Musiek (2014) make a case for use of MLR specifically by stating “… the presence of a significant MLR ear effect may indicate that the patient is at higher risk of experiencing binaural interference.”

Conclusions

There is strong and well-documented evidence of the merits of binaural advantage. In recent decades, the literature has described a phenomenon of binaural rivalry, or interference, which is described in different populations and under differing conditions. In a similar vein, for decades there has been a general inclination towards binaural amplification in cases of bilateral, symmetrical hearing loss. Justification for this lies in binaural advantage, as well as other factors such as the preference to avoid auditory deprivation. Indeed, binaural amplification is an important recommendation of consensus policy statements and preferred practice patterns of hearing aid dispensing (Hawkins et al., 1991).

Systematic review has identified eighteen studies of importance in describing this phenomenon of binaural interference. The studies report data of much variability, enough to spur considerable discussion and additional studies. For example, within these studies, binaural interference is reported to occur in as little as 0% of studied subjects, and in as many as 82% of subjects (Walden & Walden, 2005), all of which highlights the general limitations in existing studies.

Nonetheless, despite the obvious need for further studies, there is seemingly a common theme amongst these studies, one which acknowledges the phenomenon and the need for the professional community to take binaural interference into account when considering both clinical assessment and treatment. McArdle et al. (2012) measured binaural interference in 20% of subjects, while Leigh-Paffenroth et al. (2011) identified such results (using MLD) in 26% of patients. Jerger et al (1993) reports findings of 8-10% of elderly hearing aid users preferring one hearing aid. Indeed, in a publication which did not study binaural interference directly, Feuerstein (1992) demonstrated results on "ease of listening" tasks in which 21% of subjects (n=48) reported better results in a monaural listening condition as compared to binaural. While there is no data to identify the exact prevalence of binaural interference, existing research suggests that it may be within the rates reported in these studies (i.e., roughly 10-25%). Clearly, additional research is needed to refine the estimate, but future studies might also broaden our knowledge base in other ways. Age-related data can be obtained in more systematic ways. Results from recent literature such as Leigh-Paffenroth (2011) suggests avenues to engage electrophysiological measures such as MLR or tests such as MLD to study the phenomenon of binaural interference. We need additional information on the relationship between measures of behavioral and electrophysiological tests on different groups of people, such as on individuals with binaural amplification versus monaural amplification, with symmetrical sensorineural hearing loss, and symmetrical scores on a routine speech recognition test.

There are implications for the fitting of amplification on those who exhibit binaural interference which must be studied further, using both measures of electrophysiology and behavior. As binaural interference has gained attention, so too have questions been raised questioning binaural versus monaural amplification benefits. We need to heed the messages provided in the literature. However, in the words of Jerger & Martin (2006), "…focusing on the results of group comparisons often obscures the fact that elderly persons with presbyacusic hearing loss are not necessarily a homogenous group. Indeed, one of the most pervasive findings in auditory aging research is the observation that variability increases as both age and degree of hearing loss increase." Likewise, we need to critically analyze the data that exists. It is important to distinguish between those who have binaural interference and those who do not, so that we can best determine prognosis for treatment, particularly with amplification and similar devices, but also with respect to other habilitative and rehabilitative measures. As we learn more about this phenomenon, we may learn how to better manage those who currently reject amplification for no obvious reason. Indeed, we may learn that the best course of action for these individuals is to encourage monaural amplification. Alternatively, we may gain knowledge to help develop measures to offset the deleterious effects of binaural interference. At this time, from the body of literature on the topic of binaural interference that, while not yet fully understood, there are elements we can learn from and incorporate into clinical practice immediately. We must be mindful of the literature suggesting that binaural interference may occur in individuals presenting clinically. While our goals may be to continue to encourage binaural amplification so that individuals may potentially avail themselves of all or many of the known advantages of binaural listening, we must remember, too, the possibility that someone may function more poorly when listening binaurally. While widely-adopted protocols do not currently exist to manage such cases, it seems reasonable to temporarily remove the offending signal or device, assess the individual in different conditions including, possibly using electrophysiological measures, and to reintroduce in a measured manner amplification when possible. What is clear, however, is that there is great potential for future study on the phenomenon known as binaural interference.

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