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Title: Perspectives: Beyond the Pure Tone Audiogram

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Background: The pure tone audiogram, though fundamental to audiology, presents limitations, especially in the case of central auditory involvement. Advances in auditory neuroscience underscore the considerably larger role of the central auditory nervous system in hearing and related disorders. Given the availability of behavioral audiological tests and electrophysiological procedures that can provide better insights as to the function of the various components of the auditory system, this perspective piece reviews the limitations of the pure tone audiogram and notes some of the advantages of other tests and procedures used in tandem with the pure tone threshold measurement.

Purpose: To review and synthesize the literature regarding the utility and limitations of the pure tone audiogram in determining dysfunction of peripheral sensory and neural systems, as well as the central auditory nervous system, and to identify other tests and procedures that can supplement pure tone thresholds and provide enhanced diagnostic insight, especially regarding problems of the central auditory system.

Research Design: A systematic review and synthesis of the literature.

Data Collection and Analysis: The authors independently searched and reviewed literature (journal articles, book chapters) pertaining to the limitations of the pure tone audiogram.

Results: The pure tone audiogram provides information as to hearing sensitivity across a selected frequency range. Normal or near normal pure tone thresholds sometimes are observed despite cochlear damage. There are a surprising number of patients with acoustic neuromas who have essentially normal pure tone thresholds. In cases of central deafness, depressed pure tone thresholds may not accurately reflect the status of the peripheral auditory system. Listening difficulties are seen in the presence of normal pure tone thresholds. Supra-threshold procedures and a variety of other tests can provide information regarding other and often more central functions of the auditory system.

Conclusion: The audiogram is a primary tool for determining type, degree, and configuration of hearing loss; however, it only provides the clinician with information regarding hearing sensitivity, and no information about central auditory processing, nor the auditory processing of real world signals (i.e., speech, music). The pure tone audiogram offers limited insight into functional hearing and should be viewed only as a test of hearing sensitivity. Given the limitations of the pure tone audiogram, a brief overview is provided of available behavioral tests and electrophysiologic procedures that are sensitive to the function and integrity of the central auditory system, which provide better diagnostic and rehabilitative information to the clinician and patient.

Key Words: Central Auditory Processing Disorder, Auditory evoked potentials, Diagnostic techniques, Audiogram

Abbreviations:
CANS- Central Auditory Nervous System
HINT- Hearing in Noise Test
ABR- Auditory Brainstem Response
VA- Veterans Administration
IHC- Inner Hair Cells
CAPD- Central Auditory Processing Disorder
OAD- Obscure Auditory Dysfunction
SIN- Speech in Noise Test
EP- Evoked Potentials
OAE- Otoacoustic Emissions
AR- Acoustic Reflex
MLD- Masking Level Difference
FPT- Frequency Pattern Test
DPT- Duration Pattern Test
GIN- Gaps in Noise
RGDT- Random Gap Detection Test
LPFS- Low-Pass Filtered Speech
AMLR- Auditory Middle Latency Response
MMN- Mismatch Negativity
AEP- Auditory Evoked Potential

I. Introduction

In the early 1980's, the first author of this article discussed in formal and informal venues the concept of "beyond the pure tone audiogram." Though the details of these discussions have faded from memory over the years, these conversations led to a formal publication in 1986 entitled, "Hearing beyond the eighth nerve" (Musiek, 1986). This editorial highlighted the shortcoming of relying only on the pure tone audiogram to evaluate hearing status. This was especially true in light of patients who had central auditory deficits. Clinical populations with compromise of the central auditory system often reported symptoms of hearing difficulties; however, their symptoms were not reflected in what was then the standard test of hearing --- pure tone audiometry--- and its graphic representation, the audiogram.

Well before 1980, a number of reports demonstrated rather marked auditory deficits in people with central nervous system disorders; however, these deficits were only manifested on tests more complex than pure tone audiometry. Research by Bocca and his Italian colleagues, as well as by Jerger, Kimura, and Katz in the mid-to-late 1950s and early 1960s drew attention to the need for evaluating patients with central auditory lesions with audiologic tests "sensitized" to central auditory dysfunction (Bocca et al. 1954; Jerger, 1960; Kimura, 1961; Katz, 1962). These early researchers ushered in the development of new tests and demonstrated the futility of using pure tone thresholds to assess auditory compromise in patients with neuro-auditory disorders.

Over the next several decades, considerable research amassed in the area of central auditory dysfunction, and mostly by inference, the limitations of pure tone audiometry (Chermak and Musiek, 1997; Baran and Musiek, 1999; Musiek and Chermak, 2007). Several reports made

clear that changes in the CANS can also occur in individuals with hearing loss. Several studies showed that both young and older adults with bilateral symmetric sensorineural hearing loss who received a monaural hearing aid fitting experienced a progressive decrement in their word recognition scores in their unaided ear, while word recognition scores in their aided ear remained unchanged in the absence of any change in their pure tome audiograms. Individuals aided binaurally did not experience any decline in word recognition scores (Silman, Gelfand, and Silverman, 1984; Gelfand, Silman, and Ross, 1987; Hurley, 1998). These findings suggest strong central effects of auditory deprivation in the unaided ear of individuals fitted monaurally that is undetectable by the pure-tone audiogram. These studies corroborated patients' complaints of decreased hearing with no apparent change in pure tone thresholds.

The accumulating evidence of the pure tone audiogram's limitations has penetrated all aspects of audiology. In addition, advances in auditory neuroscience have begun to emphasize the considerably larger role of the central auditory nervous system (CANS) in hearing and related disorders. As a result of changing views on transynaptic degeneration, tinnitus, homeostatic plasticity, brain reorganization, and the effects of noise on the auditory system, attention has turned from almost exclusive focus on the auditory periphery to include more central mechanisms (Schwaber et al. 1993; Morest et al. 1998; Lockwood et al. 2002; Eggermont, 2012).

This change in thinking has become apparent at major audiologic conferences over the past two or three years. Featured presentations that focused on the topic of "beyond the pure tone audiogram" were well attended (AAA, 2013 [Shinn and Musiek]). More presentations than ever before have included comments referencing pure tone limitations (AAS, 2014; AAA, 2015). Audiologists now recognize the importance of assessing the central auditory system to fully

evaluate auditory or hearing function. The purpose of this article is to elaborate this point, its rationale, and its implications. While recognizing the important role of the pure tone audiogram in clinical audiology, we review data demonstrating the shortcomings of pure tone threshold testing in the broader context of assessing overall hearing status. The audiogram's appropriate use will be discussed, including the role of threshold versus supra-threshold measures. Next, several unique studies are highlighted to demonstrate that audiograms do not always reflect damage to the cochlea –a finding seemingly counterintuitive. This is followed by a section devoted to reports of various degrees of auditory symptoms and difficulties presented by individuals with normal pure tone audiograms, reflecting an important disassociation between the pure tone audiogram and patient complaints. Next, we discuss the finding, although seen in only a minority of cases, of normal pure tone thresholds in those with auditory nerve involvement. We continue with a review of the initial impetus for testing beyond the audiogram ---- central auditory involvement--- and conclude with a brief overview of available tests and procedures that assess the central auditory system, which in some instances also may provide insight into the function of the auditory periphery.

II. Value of the Audiogram

There is no denying that pure tone audiometry has become the hallmark measure in the evaluation of patients with hearing disorders. It serves as a critical tool in the diagnosis of many audiological and otologic disorders. It is important in providing information regarding type, degree, and configuration of hearing loss. Additionally, it has vital diagnostic value in assisting physicians in making surgical decisions. The audiogram is an old tool, however, and has advanced relatively little over the years. As noted by Feldmann (1970), audiometric related

events date back to 377 BC when Hippocrates reported clinical findings of hearing loss. Richardson coined the word "audiometer" in 1879, with Hartmann creating the first "auditory chart" in 1885 (Vogel et al. 2007). The first audiometers were manufactured in the 1930s, and while substantial technological advancements have occurred since (e.g., computer-based platforms), the fundamental technical and diagnostic principles underlying audiometry have remained essentially unchanged over the last 50+ years.

As audiologists, we are charged with evaluating, diagnosing, and treating an array of disorders of the auditory and vestibular systems. To do so requires that we understand the intricacies of the anatomy and physiology of these systems. While most audiologists are relatively well versed with respect to peripheral anatomy and physiology, fewer have the same depth of knowledge of the central auditory nervous system (CANS). As a result, many audiologists are less comfortable with neuroaudiologic assessment and rehabilitation. As Chermak and colleagues documented in 2007, too few audiologists evaluate central auditory function, a situation which has improved somewhat in the last decade, although based on the inquiries the authors and their colleagues receive on a regular basis, locating an audiologist with this expertise can be challenging, especially in certain parts of the authors' home countries, the United States and Great Britain.

The audiogram is excellent at determining degree and configuration of hearing loss, and in conjunction with other basic audiologic tests (e.g., immittance and speech audiometry) helps determine the type of hearing loss. However, the audiogram only provides the clinician with information regarding hearing sensitivity, and no information about central auditory processing (despite the fact that pure tone signals do reach the primary auditory cortex). Nor does the pure

tone audiogram provide any information regarding the auditory processing of real world signals (i.e., speech, music). The CANS is an intricate neural communication network that plays a vital role in hearing. In fact, patients with CANS compromise (e.g., auditory agnosia) can present marked deficits in auditory processing despite normal audiograms and usually, relatively normal hearing sensitivity (Kazui et al. 1990). (Also see discussion of central deafness below). As our profession advances, so should our view and approach to diagnostic assessment and rehabilitation of the total auditory system, not simply the periphery.

A prime example of our professional transition away from the dependency on the audiogram is the evolution of candidacy criteria for cochlear implant recipients. During the early years of cochlear implants, only profoundly hearing impaired patients were considered candidates. In more recent years, candidacy guidelines have become significantly less stringent allowing patients with lesser degrees of hearing impairment to satisfy eligibility requirements. Perhaps even more important, however, is that functional performance in noise (e.g., using tests such as the Hearing in Noise Test (HINT) and AzBio test (Nilsson et al. 1994; Spahr et al. 2012) is given significantly more weight than pure tone thresholds in determining eligibility for a cochlear implant.

The pure tone audiogram is considered to offer limited insight into functional hearing and is therefore not considered to provide the most ecologically valid information regarding auditory function in real world settings. There are numerous examples in the literature demonstrating that patients who present with CANS involvement may, and often do, yield normal auditory thresholds. As early as 1942, Karlin reported that the audiogram was a poor predictor of

performance in complex listening environments. An example of the failure of the audiogram to reveal evidence of higher auditory dysfunction also was observed by Bocca and colleagues in the 1950s (Bocca et al. 1954, 1955). Bocca's work confirmed that patients with lesions of the CANS often present with normal audiograms, despite significant deficits with respect to processing degraded speech. This would have been undetected if the audiogram were the only test used to evaluate the auditory system.

Perhaps some of the most compelling examples of the limitations of the audiogram are seen in patients who present with central deafness (Musiek and Lee, 1998; Musiek, Baran, Shinn, Guennette, Zaidan, & Weihing, 2007). Musiek and colleagues (2007) described a patient who presented with bilateral cerebrovascular accidents. The pure tone audiogram revealed a severe to profound hearing loss bilaterally; however, further examination using otoacoustic emissions, acoustic reflexes, and the auditory brainstem response (ABR) revealed normal function, bilaterally. Of note, however, was the finding that the middle and late auditory potentials were severely compromised. This case underscores the need to examine the entire auditory system, using a variety of behavioral tests and electrophysiological procedures, and the importance of a thorough understanding of the anatomical structures involved in the measured responses. Had the entire auditory system not been thoroughly evaluated, this patient might have been inappropriately fit with amplification or even a cochlear implant, only to experience limited benefit at best. Even more serious than not having benefited the patient, inappropriately providing a cochlear implant might well have unnecessarily and inadvertently obliterated a normal functioning cochlea.

More recently, the Veterans Administration (VA) has examined auditory deficits in veterans return from recent military operations (i.e., Operation Iraqi Freedom/Operation Enduring Freedom/Operation New Dawn [OIF/OEF/OND]). Specifically, the VA has examined veterans with blast-related injuries (Lew et al. 2007; Gallun et al. 2012; Oleksiak et al. 2012; Saunders and Echt, 2012; Saunders et al. 2015). Many of these veterans have expressed concerns regarding their hearing, particularly in noisy situations or less than ideal listening environments; however, they present with normal peripheral hearing sensitivity. These findings led Gallun and colleagues (2012) to compare veterans with and without blast related injuries. Those that were blast-exposed demonstrated significant deficits in temporal resolution, binaural integration, and speech recognition in noise compared to the control group. In addition, they demonstrated differences in objective electrophysiological measures. While the ABR did not reveal significant differences between groups, the blast-exposed group demonstrated both latency (delayed) and amplitude (reduced) differences in the right ear on late auditory evoked potentials (P300) relative to the control group. Saunders et al. (2015) examined 99 blast-exposed veterans through self-report and behavioral measures. The most common deficit was speech-in-noise difficulties (>75%). More than half of the veterans presented deficits on 3 to 6 of the 10 functional measures that were administered (e.g., HINT, North American Listening in Spatialized Noise-Sentence Test, Staggered Spondaic Words, etc.). Their confirmed blast injuries likely contributed to their central deficits, further demonstrating why one cannot rely solely on the audiogram to comprehensively assess the auditory system. Further demonstrating the limitations of the pure tone audiogram in revealing the underlying status of the auditory system, Saunders and Echt (2012) found that more than half of VA audiologists (53%) reported encountering 2-3 veterans

per month reporting auditory complaints, despite normal audiograms, with nearly all VA audiologists (93%) reporting at least one veteran per month with that profile.

In fact, self-reported hearing difficulties among adults with normal audiograms is not confined to veterans. Shinn and colleagues recently reported on patients seen in a general audiology/Otolayrngology clinic. Of those patients who presented with concerns regarding hearing despite having normal audiograms, 13% specifically reported auditory processing deficits (as reflected by their challenges hearing in noise and in difficult listening environments), and 48% were concerned about hearing loss (Shinn et al. 2016). Those with concerns regarding "hearing loss" were more than likely experiencing some degree of abnormal auditory perception that requires further evaluation for identification and treatment planning.

Additional evidence of the limitations of the audiogram arises from studies of patients with tinnitus and those exposed to noise. A number of studies have shown that patients with tinnitus present with subtle audiological deficits not observed on the audiogram (Schaette and McAlpine, 2011; Epp et al. 2012; Ishak et al. 2013). Moreover, subtle auditory deficits of both the peripheral and central mechanisms due to noise exposure have been observed on otoacoustic emissions (OAEs) (Boger et al. 2012), sound localization (Menezes et al. 2014), and temporal processing (Kumar et al. 2007), despite the presence of normal hearing sensitivity (as reflected on the audiogram).

III. Normal pure tone thresholds and cochlear damage

Conventional thinking posits that the pure tone audiogram reflects the functional status of the cochlea. This certainly is supported, at least partially, by studies showing elevated pure tone thresholds in cochleas with damage to hair cells (Schuknecht, 1974). However, over the years, a few reports have demonstrated that this correspondence may not be absolute. For example, fifty years ago a classic histological study of the cochlea questioned the degree to which histological damage to the hair cells correlated with pure tone thresholds, thereby casting some doubt on the physiological validity of pure tone thresholds (Bredberg et al. 1965). Hunter-Duvar and Elliott (1972) reported normal thresholds in a squirrel monkey with considerable hair cell loss. Ward and Duvall (1971) reported on two animals with normal pure tone thresholds despite marked hair cell damage at the basal and middle turns of the cochlea. Clark and Bohne (1986), examining damage from low frequency, high intensity sound exposure to the apical section of the cochlea of chinchillas, concluded that up to 50 percent of the hair cells could be missing without significantly affecting the animal's low frequency hearing sensitivity. Though these authors reported better correlations between pure tone thresholds and hair cell integrity at the basal turn of the cochlea, they interpreted their overall results as reflecting the insensitivity of the pure tone audiogram to cochlear histology. Following additional analyses, Clark and Bohne concluded that "pure tone thresholds are not adequate to determine functional status of the ear" (p. 78). More recently, Lobarinas et al. (2013) made a similar observation following carboplatin damaged inner hair cells (IHCs) in chinchillas (N=9). They reported only minimal shift in pure tone thresholds, with most frequencies remaining within normal range, even when inner hair cell damage approached 80% of the total number of IHCs. Lobrinas et al. concluded that there was poor correlation between loss in IHCs and pure tone thresholds. As is now known, IHCs are not, for the most part, sensitive to low intensity, but rather are activated at high intensities (Kujawa and

Liberman, 2009). Notwithstanding this distinction, Lobrinis et al.'s findings further demonstrate the limitations of pure tone threshold procedures. A number of studies preceding those mentioned here also commented on the presence of normal or near normal pure tone thresholds despite cochlear damage. These studies primarily examined auditory neurons absent secondary to hair cell damage. Because these investigations focused on auditory nerve fibers, they are reviewed in the next section on the auditory nerve.

While audiologists often assume that abnormal pure tone thresholds reflect damage to the cochlea ---usually the hair cells---this may not be accurate in all cases. Indeed, in the absence of histological data, such as in a clinical situation, we are left to infer the status of the hair cells and cochlear dysfunction based on pure tone thresholds. However, this may lead to incorrect inferences. Clearly, there is a relationship between pure tone thresholds and hair cell damage; however, in many instances of hair cell depletion, pure tone thresholds do not accurately reflect the degree of depletion, and in fact, may not reflect hair cell depletion at all, as seen by essentially normal hearing sensitivity. The reports of basic scientists suggest the need for assessment tools beyond pure tone audiometry to monitor hair cell damage and the status of the cochlea (Clark and Bohne, 1986).

IV. Normal pure tone thresholds and auditory nerve compromise

Considerable evidence confirms that damage to the auditory nerve results in loss of hearing sensitivity and elevated pure tone thresholds, as seen in cases of vestibular schwannomas (i.e., acoustic tumors). In fact, it has been reported that approximately ¾ of patients with acoustic tumors present unilateral, high frequency sensorineural hearing loss, with various other

audiometric configurations (including normal thresholds) constituting the remaining 25 percent (Johnson, 1977). Indeed, there are a surprising number of patients with acoustic neuromas who have essentially normal pure tone thresholds. One of the first reports that pure tone thresholds might not consistently reveal dysfunction of the auditory nerve was published by Crowe et al. (1934) who studied human temporal bones from individuals with documented normal pure tone thresholds. Crowe et al. reported considerable auditory nerve atrophy (up to 50%) at the basal turn, which was considered to be secondary to hair cell damage in this region. Schuknecht and Wollner (1953) reported normal detection thresholds in one of three cats who had ~ 80% of their spiral ganglion cells destroyed. In a follow up study on cats, Schuknecht and Wollner (1953) reported that 50% of spiral ganglion cells could be damaged without a shift in normal pure tone thresholds. Subsequently, other animal studies have reported normal pure tone thresholds despite extensive damage to spiral ganglion cells (Elliott, 1962).

In a review of several extensive studies of humans with confirmed acoustic neuromas, 72 (or 5%) of a total of 1,685 patients presented normal pure tone thresholds for the involved side (Beck et al. 1986; Dornhoffer et al. 1994; Kanzaki et al. 1997; Magdzoarz et al. 2000; Mackle et al. 2007). This figure of 5% is consistent with estimates by others (Musiek, Kibbe-Michal, Guerkink, Josey, & Glasscock, 1986). In these studies, the criteria for normal pure tones thresholds varied from lax (normal thresholds for frequencies 500 - 2000 Hz; <25 dB HL) to strict (250 – 8000 Hz; < 20 dB HL and no more than 10 dB asymmetry). Of note was one study that reported a 5% rate of normal pure tone hearing thresholds; however, of this group of 21 patients with acoustic tumors and normal thresholds, 13 reported subjective hearing loss (Beck et al. 1986), a finding generally consistent with the report by Musiek et al. (1986). Musiek and colleagues (1986) reported hearing loss or hearing difficulties in 12 of 16 patients with

cerebellopontine angle tumors and essentially normal pure tone thresholds. In another study, Day et al. (2008) reported that 11% of their patients with acoustic neuroma presented normal pure tone thresholds. Other studies may not have reported a prevalence rate, but did conclude that pure tone thresholds could be normal in the presence of acoustic neuromas and urged the use of other measures beyond the audiogram (Musiek et al. 1986; Valente et al. 1995).

With the exception of one study (Beck et al. 1986), our review does not account for those who have symmetrical hearing loss, and therefore, likely reveals the lack of sensitivity of pure tone thresholds to the acoustic tumor and auditory nerve involvement. For example, one study reported that 7% of their patients with acoustic neuromas revealed symmetrical pure tone thresholds (Selesnick and Jackler, 1993). It seems likely that if all studies had looked at both normal and symmetrical hearing thresholds in their patients with acoustic neuroma, the frequency with which acoustic neuromas did not influence pure tone thresholds would be even higher.

Kujawa and Liberman (2009) reported interesting findings in mice relative to auditory nerve involvement and pure tone thresholds after noise exposure. The animals' pure tone thresholds resolved to normal following temporary threshold shift; however, the animals incurred damage to afferent auditory nerve terminals and subsequent degeneration of the auditory nerve. Kujawa and Liberman noted that pure tone audiograms did not reflect the overall and progressive damage to hearing in these animals. They also demonstrated that the ABR revealed auditory nerve dysfunction and was, therefore, a more accurate index of the animal's true hearing status.

These animal and human reports reveal that most auditory nerve compromise is reflected by pure tone shift; however, this correspondence is not consistent, despite the widespread

assumption that it is. Normal pure tone thresholds can be seen despite damage to or pathology of the auditory nerve. Clearly, clinicians investigating acoustic neuromas should include measures in addition to pure tone thresholds to more accurately evaluate hearing in such patients (Musiek et al. 1986; Valente et al. 1995).

V. Auditory symptoms of individuals with normal audiograms

Since the seminal observations of Bocca et al. (1954), we have known that patients with brain pathology may complain of hearing difficulties despite the presence of normal hearing thresholds and normal speech recognition in quiet. As part of a psychoacoustic pattern discrimination test validation study, Blaettner et al. (1989) administered a hearing questionnaire to patients with unilateral cerebrovascular lesions of the telencephalic auditory structures to assess potential auditory perceptual problems in everyday hearing situations. They found that about half (49%) of their patients reported auditory perceptual problems, particularly in situations with simultaneous speakers; however, the vast majority (79%) of those patients who gave abnormal results on the psychoacoustic test reported auditory perceptual problems. Of interest, the latter patients often stated that they did not have any hearing complaints prior to the questionnaire being administered. This is consistent with our own anecdotal observations that neurological patients with self-reported difficulties in several hearing activities (e.g., localization, understanding speech in noise, perception of music), may not attribute these difficulties to hearing, since their ability to hear soft sounds may be unimpaired. Blaettner et al. (1989) proposed that the reduced ability of patients with central auditory lesions to follow or select a

speaker in a noisy environment is similar to the disability experienced by individuals with a peripheral (cochlear) hearing loss, and this central auditory disability should be taken into account when evaluating the communication abilities of patients with brain lesions. Bamiou et al. (2012) administered the modified Inventory for Auditory Disability questionnaire (Kramer et al. 1995) to 21 non-aphasic adult patients with stroke of the auditory brain regions and relatively preserved audiometric thresholds and 23 normal age- and hearing-matched controls. Stroke patients' scores for sound recognition and localization were significantly worse than scores for normal controls. Moreover, the questionnaire scores correlated significantly with the results of central auditory processing test scores, but not with hearing thresholds. Bamiou et al. (2012) proposed that the questionnaire could help identify stroke patients who need further audiological assessment for central auditory processing disorder (CAPD).

Listening difficulties in the presence of normal pure tone thresholds are not confined to those with neurological type lesions or presentations. In non-neurological cases, approximately 4% of working age adults (Hind et al. 2011) and up to 10% of all adults (Kumar et al. 2007) who present to audiology clinics with complaints of significant listening difficulties have normal pure tone thresholds. A proportion of these patients demonstrate abnormal performance on complex psychoacoustic tests, and when their auditory nerve function is intact, their presentation is attributed to CAPD. Saunders and Haggard (1992) conducted a study to characterize patients (whom they classified as having obscure auditory dysfunction (OAD), as discussed below in the section titled—Limitations of the Audiogram with Other Populations) with difficulties in hearing speech-in-noise, and determine the etiology of their symptoms. The study protocol included hearing tests (e.g., pure-tone audiometry, frequency resolution, speech-in-noise (SIN) test, a

sentence completion task, and a lip-reading test), as well as psychological assessments (i.e., a personality questionnaire and hearing difficulties questionnaire). They showed that these patients differed significantly from the controls in three domains: (1) psychological domain (i.e., greater anxiety on personality test), (2) psychoacoustic domain (i.e., impaired frequency resolution, SIN threshold), and (3) cognitive/linguistic domain (i.e., lower scores on the focused attention condition of a dichotic listening test). They also reported that while patients with OAD and normal pure tone hearing thresholds usually were discharged from audiology departments, the finding of a normal audiogram did not satisfy these patients who subsequently sought a second opinion and further assessments. Their research led to the development of a package of performance tests, questionnaires and protocols for counseling (Saunders, Field, and Haggard, 1992). Higson et al. (1994) in a further study of 59 new OAD patients replicated the findings of the previous study by Saunders and Haggard (1992) and proposed that such patients had a consistent profile of poorer speech reception threshold (SIN) and considered themselves handicapped by their symptoms.

Neijenhuis et al. (2003) assessed hearing disability in 24 otherwise neurologically normal adults with a suspected CAPD (i.e., patients who complained of hearing difficulties on the Amsterdam Inventory (Kramer et al. 1995) despite the presence of a normal audiogram and speech recognition in quiet audiometry). Sixty-eight percent of these adults gave abnormal results (scores below the 90th percentile of the normal control group) on the central auditory test battery. As a group, the subjects with a suspected CAPD reported significantly more complaints regarding hearing abilities than normal controls for all five factors assessed by the Amsterdam Inventory, with speech in noise and sound localization as the most frequently reported

difficulties. Bamiou et al. (2015) assessed hearing symptoms in adult patients with CAPD (N=39) vs. controls (N=19) as revealed on the Speech Spatial Qualities hearing scale (SSQ) (Gatehouse and Noble 2004), the (Modified) Amsterdam Inventory for Auditory Disability (mAIAD) (Kramer et al. 1995) and the Hyperacusis questionnaire (HYP) (Khalfa et al. 2002). Speech in noise emerged as the key issue for these patients.

VI. Pure Tone Thresholds and Compromise of the Central Auditory Nervous System

The limited sensitivity of pure tone thresholds to cochlear and eighth nerve damage certainly reduces their utility in clinical evaluations of hearing function. The disassociation between patient reports of hearing difficulties with CANS involvement despite normal pure tone thresholds has become a reasonably well known and accepted finding. This lack of correspondence was revealed in early studies by Bocca and his colleagues (Bocca et al. 1954). A principle assertion of these germinal studies was that pure tone thresholds were of little value in measuring auditory deficit in patients with central auditory compromise. This understanding led these early investigators to embark on developing new test procedures that were more sensitive to detecting central auditory dysfunction. This understanding continues to guide the development of central auditory tests to better reveal with more objective measures the source(s) of the auditory symptoms of the patient with central auditory involvement (Musiek et al. 1994).

Though Bocca and colleagues' early studies began to raise awareness of the shortcomings of pure tone thresholds in revealing central auditory dysfunction, the results of other early reports

were perhaps even more striking. These reports profiled individuals who had undergone hemispherectomies and resections of major portions of the temporal lobe with essentially no effects on the pure tone audiogram (Goldstein et al. 1956; Berlin et al. 1972). The Goldstein et al. (1956) report was especially compelling in that pure tone thresholds for 4 patients with infantile hemiplegia did not significantly change from pre-operative levels after hemispherectomy. While we now know that brain plasticity could be operating in these patients, this was an important early report calling attention to the insensitivity of pure tone thresholds to a major insult to the central nervous system and the auditory cortex. It should be mentioned that one of these patients was tested several years later with degraded speech stimuli and showed a clear deficit in the ear contralateral to the hemispherectomy, demonstrating the potential of more sensitized stimuli and tests to more accurately reflect the status of the CANS.

In the 1960's and 1970's, additional reports emerged corroborating the extremely limited value of pure tone thresholds in measuring central auditory integrity. At the same time, sensitized tests such as monaural low-redundancy speech and dichotic listening began to demonstrate their worth in evaluating those with central auditory disorder (Jerger, 1960; Kimura, 1961; Lynn and Gilroy, 1972; Jerger and Jerger, 1975; Speaks et al. 1975). Such reports helped to persuade some audiologists, whether or not they worked in the area of central auditory disorders that pure tone thresholds simply do not reflect deficits of the CANS and that different test approaches and strategies are required for thorough and accurate evaluation of these patients.

Over the last 30 years, additional tests of the CANS have been developed. In a large study of consecutive patients with a wide variety of brainstem lesions and after excluding

patients with cerebellopontine angle lesions or acoustic neuromas as well as patients with hearing loss attributable to other causes (N= 309), only 26% presented pure tone thresholds poorer than 30 dB ISO (Luxon, 1980). This figure represents a "high" estimate given the study's skewed population, as they were presented to a tertiary care Neurology Neurosurgery specialist hospital. Furthermore, diagnosis of brainstem pathology was based on clinical neurological and otological grounds in all patients, and diagnosis was confirmed at operation or post-mortem examination in 35%, i.e. a sample with a high prevalence of advanced or life threatening brainstem pathology to merit operation. Conversely, a series of studies has documented the rather ubiquitous finding of the sensitivity of a variety of sensitized central auditory tests to compromise of the brainstem auditory pathway in the absence of any consistent influence on the pure tone audiogram. For example, masking level differences (MLD) have been shown to be abnormal in brainstem lesions despite normal audiometric thresholds (Olsen and Noffsinger, 1976; Lynn et al. 1981; Noffsinger et al. 1985). Similar findings were observed using interaural timing tasks in individuals with brainstem involvement (Furst et al. 2000; Aharonson and Furst, 2001; McCullagh and Bamiou, 2014). Studies using low-redundancy speech tests on patients with brainstem involvement showed no poorer than moderate hearing loss, with many of these individuals presenting normal or near normal pure tone sensitivity (Jerger and Jerger, 1974; Karlsson and Rosenhall, 1995). Dichotic listening studies also have demonstrated good sensitivity to brainstem disorders despite normal or near normal pure tone findings (Musiek, 1983).

Testing beyond the pure tone audiogram may include electrophysiological procedures as well as the behaviorally sensitized tests. The auditory brainstem response (ABR) is a powerful

measure of auditory brainstem pathway integrity, which as discussed above, is seldom reflected in pure tone thresholds (Luxon, 1980; Musiek and Guerkink, 1982; Musiek, Shinn, & Jirsa, 2007). Patients with multiple sclerosis demonstrate the insensitivity of the audiogram to brainstem integrity. Although it has been well documented that ABRs are commonly abnormal in patients with multiple sclerosis due to involvement of the auditory brainstem pathways (Paludetti et al. 1985; Musiek et al. 1989), their pure-tone auditory thresholds are rarely elevated (Doty et al. 2012). The ABR also is highly sensitive and specific to various brainstem disorders, whether they are vascular, mass, or degenerative in type, yet pure tone thresholds provide essentially no diagnostic insight to the patients' auditory problems (Musiek and Geurkink, 1982; Noffsinger et al. 1982; Musiek et al. 1988; Musiek, Shinn & Jirsa, 2007). If the pure tone thresholds were used exclusively in these cases of brainstem involvement, the overwhelming majority of patients' auditory difficulties would remain undocumented. In fact, normal pure tone thresholds at times could provide a false sense of security to the examiner who might be inclined to dismiss the patient's symptoms when in actuality the auditory system may be compromised.

Earlier in this section, it was mentioned that initial reports of normal pure tone thresholds in cases of hemispherectomy were critical in gaining insight and providing momentum in the evolution of our understanding of the need to move beyond the pure tone audiogram. Perhaps the best illustration of the shortcomings of pure tone thresholds are reports showing the absence of pure tone threshold changes from lesions of auditory areas of the cortex or cerebrum (Musiek et al. 1994; Hurley and Hurley, 2014). In many studies examining auditory cortex involvement and use of central auditory tests, patients typically were required to have normal hearing sensitivity to qualify for the study. These patients' central auditory test performance was clearly abnormal

due to their documented lesions of the auditory cortex. Major strokes and related vascular problems, head injury, mass lesions, and degenerative disorders of the auditory cortex have been shown to yield abnormal results on a myriad of behavioral test procedures, including temporal processes (Musiek et al. 1990; Baran and Musiek, 1999; Musiek et al. 2005; Musiek et al. 2012; Shinn, 2014), dichotic listening (Musiek, 1983; Musiek et al. 2012; Weihing and Acherson, 2014), low-redundancy speech (Lynn and Gilroy, 1972, 1977; Krishnamurti, 2015), and binaural interaction procedures (McCullagh and Bamiou, 2014).

In addition to the ABR, other electrophysiological procedures (e.g., middle latency and late auditory evoked potentials [EPs]) tell a similar story. These EPs are sensitive to cortical damage to the auditory areas and in most cases are accompanied by a normal audiogram (Knight et al. 1980; Musiek et al. 1994; Musiek et al. 1999; Musiek and Lee, 1999). Though middle and late EPs are not, in most cases, routine clinical procedures, in the right situations they are valuable and can provide diagnostic insight well beyond the capability of the pure tone audiogram.

VII. Limitations of the Audiogram with Other Populations

Over the years, there has been a series of reports of individuals with normal pure tone thresholds with presumed damage to the CANS (based on symptoms such as difficulty understanding speech in background noise) or possibly damage to the cochlea. These individuals presented performance deficits on more complex auditory tests. For example, elderly participants presented a decrease in speech recognition in noise over time in the absence of any change in the pure tone audiogram (Dubno et al. 1984*).* Similarly, there have been reports of changes in

temporal processing ability with increasing age with essentially no change in pure tone thresholds (He et al. 2008; Hopkins and Moore, 2011*).* Age-related reductions in the brainstem frequency following response (FFR) synchrony and amplitude, as well as prolonged latencies, have been observed in middle age individuals, even in the absence of significant hearing loss (Clinard and Tremblay, 2013). Based on recordings of speech-evoked ABRs in quiet and in noise in older adults with normal hearing sensitivity, Anderson et al. (2011) reported that those older adults with poor speech recognition in noise performance demonstrated greater disruption of response morphology in noise, reflecting a reduction in neural synchrony.

Another population commonly seen by audiologists is children with normal hearing sensitivity with CAPD and language related learning problems in the absence of frank underlying neuropathology (Bishop, 2000). A number of studies suggest that at least some of these children present with some underlying benign, diffuse or focal neuroanatomic/neuromorphological abnormalities (e.g., ectopias [normal but misplaced cells]), polymicrogyria [abnormally small gyri]) or maturational delay due to a slower course of myelination or auditory deprivation (Galaburda et al. 1985; Boscariol et al. 2009; Boscariol, Garcia, Guimarãesa et al. 2010; Boscariol, Guimarãesa, de Vasconcellos Hage et al, 2010; Boscariol et al., 2011; Chermak and Musiek, 2011; Boscariol et al., 2015). This pediatric population has characteristically been defined by normal pure tone thresholds, the presence of auditory symptoms, and related learning difficulties. They also show deficits on central auditory tests. These children can be helped by various intervention techniques, as the recent literature has shown (Musiek et al. 2014; Weihing and Musiek, 2014). Again, if only a pure tone audiogram

were obtained on these children, there might be no documentable reason to pursue intervention. Unfortunately, this failure may occur more often than we might wish to acknowledge.

Based on the animal work of Kujawa and Liberman (2009) and Pienkowski and Eggermont (2012), it appears that noise exposure can result in damage beyond the cochlea without affecting the pure tone audiogram. Alvord (1983) reported that individuals with a history of noise exposure and normal audiograms still demonstrated poorer speech recognition in noise scores than did a control group not exposed to noise. Despite a methodological concern (i.e., the noise group had slightly more loss at 4 kHz than the control group), Alvord's study contributed to the early seeds of thought concerning the inability of the pure tone audiogram to reflect damage to the auditory system, whether that damage was peripheral or central. A striking study published in 2012 by Kumar et al. compared a group of noise exposed workers with normal pure tone audiograms to a matched control group without a history of noise exposure. Though the audiograms were essentially the same across groups, the noise-exposed group performed more poorly on (temporal) tests of modulation detection and duration pattern perception (generally considered a measure of central auditory function). Kumar et al.'s results could be interpreted to suggest that noise damaged the central auditory system but not the cochlea, or that the noise damaged both peripheral and central systems, but the audiogram did not reflect the peripheral auditory compromise.

Recently published data reveals how exposure to moderate levels of noise over long durations can precipitate tonotopic disorganization in the cortex of cats (Pienkowski and Eggermont, 2012). This cortical compromise evolves without affecting detection thresholds. These findings again demonstrate the failure of audiometric threshold measures to provide any

insight as to what appears to be devastating dysfunction of the cortex. Clinically, these data suggest that a patient with a history of noise exposure could experience degraded frequency processing that could affect overall hearing function, which would not be heralded by any pure tone threshold changes. Again, clinicians should adopt a cautious approach in rendering a diagnosis of "normal hearing" based solely on the pure tone audiogram.

VIII. When the Pure Tone Audiogram Bears Little if Any Relevance to Peripheral Integrity

We have discussed the limitations of the pure tone audiogram to reveal damage to the cochlea (as well as the CANS). Central deafness provides a fascinating condition where the pure tone audiogram may in fact reflect massive dysfunction of the CANS without any relevance to peripheral integrity. Indeed, pure tone thresholds may be absent in complete central deafness or show severe decrements in central deafness; however, the source of these deficits in sensitivity is central in origin: they do not originate in the peripheral auditory system (Musiek, Baran, and Pinheiro, 1994; Musiek, Baran, Shinn, Guenette, Zaidan, & Weihing, 2007). In fact, the term central deafness is preferred to central hearing loss since the term hearing loss implies a peripheral origin. Typically, OAEs are present which suggests normal cochlear function (i.e., outer hair cell function), or at most a mild hearing loss, as well as normal ABRs which confirm the integrity of the inner ear and cochlear nerve, as well as the auditory pathways within the low brainstem. Speech recognition typically is severely depressed--often more severely depressed than predicted based on pure tone thresholds (Kaga et al. 2004). Evoked potentials that assess electrophysiological responses that originate in the cortex or the radiations to the auditory cortex reveal abnormalities in central deafness and complete central deafness (Musiek et al. 2004).

Typically, patients can speak, read, and write. Auditory deficits (e.g., pure-tone thresholds, patient's assessment of 'hearing') typically are poorer in the ear contralateral to the hemisphere with the most damage (Heffner and Heffner, 1986; Musiek et al. 1994). Inconsistent responses to sound may result from attention deficits, or improper triggering of attention by ascending auditory tracts (Musiek et al. 1994).

IX. Central Auditory Tests and Procedures

Given the limitations of the pure tone audiogram, we provide a brief overview of available clinical, behavioral tests and electrophysiological procedures that are sensitive to the function and integrity of the central auditory system and are useful for clinical evaluation and diagnosis of CAPD. Tests reviewed include those of dichotic listening, binaural interaction (e.g., masking level differences), temporal processing (e.g., temporal resolution and temporal patterning), and monaural low-redundancy measures (e.g., speech in noise or competition, filtered speech, time compressed speech). Current and new paradigms involving measurement of auditory evoked potentials also are mentioned. Finally, we note the potential of software to develop behavioral tests to assess auditory functions for which there are no or few commercially available options. The reader is referred to Weihing et al. (2015) and Musiek, Chermak, Weihing, Zappulla, & Nagle, (2011) for discussion of the sensitivity and specificity of the tests reviewed below. The reader is referred to Musiek and Chermak (2014) and AAA (2010) for detailed reviews of the tests and procedures outlined below.

Though primarily considered a test of cochlear function, OAEs, whether transient or distortion product, can assist in the diagnosis of central auditory involvement (Musiek and

Chermak, 2015). OAEs usually are absent or abnormal when cochlear hearing loss exceeds 30 dB HL for transient OAEs and approximately 40 dB HL for distortion product OAEs. Though it is well known that auditory nerve function is not necessary for generation of OAEs, VIII nerve disorders such as acoustic tumors can disrupt OAEs.

The acoustic reflex (AR) and other audiological tests (e.g., air and bone conduction thresholds, tympanometry, and reflex decay) can help differentiate middle ear, cochlear, and eighth nerve problems; however, these tests are not able to differentiate auditory nerve from low brainstem involvement. The AR is mediated in the lower pons, and, therefore, reflects only a small portion of the CANS. The AR, however, can provide insight as to central auditory dysfunction in the caudal brainstem (Musiek and Chermak, 2015). AR abnormalities have been observed in only a relatively small portion of the children with CAPD. This observation suggests that the central dysfunction underlying their CAPD was rostral to the brainstem (Hall and Johnston, 2007). Abnormal AR findings, however, have been reported in a number of different central auditory disorders with established brain pathology, such as tumors of the brainstem (Jerger and Jerger, 1977), multiple sclerosis (Jerger et al. 1986), head injury (Hall et al. 1982), and more recently in lead poisoning (Counter et al. 2011).

Dichotic listening (i.e., listening to different acoustic events presented to each ear simultaneously) is among the most widely used behavioral tests of the CANS and central auditory processing. The most commonly used clinical tests employing the dichotic paradigm are the: Staggered Spondaic Word (SSW) test (Katz, 1962), Dichotic Digits (DD) (Musiek, 1983), the competing words and competing sentences subtests of the SCAN-3:C Tests for Auditory

Processing Disorders for Children (SCAN-3:C) (Keith, 2009) and of the SCAN-3:A Tests for Auditory Processing Disorders in Adolescents and Adults (SCAN-3:A) (Keith, 2009), and Dichotic Words (DW) (Meyers et al. 2002). In patients with well-localized lesions, the ear contralateral to the involved hemisphere often exhibits poor performance relative to norms (intersubject) or to the other ear (intrasubject, inter-aural comparison) (Kimura, 1961; Musiek, 1983; Musiek and Weihing, 2011). If the corpus callosum is involved, a left ear deficit is seen consistently (Musiek and Weihing, 2011). A left ear deficit also is seen in young children (under 12 years) whose corpus callosum not yet have attained their full complement of myelin, as well as in the elderly and in individuals with diseases affecting myelin (e.g., multiple sclerosis) (Musiek et al. 1984; Musiek and Pinheiro, 1985; Musiek and Weihing, 2011). However, there are well established top-down cognitive effects on such tests that reflect the interaction of auditory processing with auditory cognition (e.g., Jerger and Martin, 2006; Martin, Jerger, and Mehta, 2007; Gates et al. 2010; Davis et al. 2012).

Binaural interaction tasks require the listener to combine complementary inputs distributed between the ears, synthesizing intensity, time, or spectral differences of otherwise identical stimuli presented simultaneously or sequentially (e.g., localization and lateralization tasks) to the two ears. Localization refers to the identification of the location of a sound source in a sound field. Lateralization is a similar process in which the individual determines the location in the head (intracranial) of a sound image presented through headphones. The effects of brain lesions on sound localization have been demonstrated extensively in animals and humans. Damage to the CANS (as well as peripheral hearing loss) reduces the ability to accurately localize a sound source (Bamiou, 2007). No clinical measure of localization has been adopted

clinically. However, a binaural interaction task, masking level differences (MLD), is used clinically and reveals an individual's ability to detect a target signal (usually low frequency tones or speech) in noise when the binaural phase relationships between the signal and noise are altered. Noffsinger et al. (1972) demonstrated a decrease in the MLD relative to norms in a large population of patients with multiple sclerosis, which primarily affects the central auditory pathway. Lynn et al. (1981) reported that patients with low pontine lesions presented smaller MLDs than controls or those with lesions of the upper brainstem or cortex, demonstrating the differential sensitivity of MLDs to various anatomical regions of the CANS. The Listening in Spatialized Noise--Sentences (LisN-S) (Cameron and Dillon, 2007) test offers another approach to examine binaural interaction and correlates well with the MLD (Cameron et al. 2006). An added benefit of this test is that it provides a derived measure for voice and spatial cue, thus minimizing, if not entirely eliminating linguistic influence on test performance.

Auditory temporal processing refers to the perception of sound or the alteration of sound within a restricted or defined time domain (Musiek et al. 2005). Temporal processing is comprised of: 1) temporal ordering or sequencing, 2) temporal resolution or discrimination, 3) temporal integration or summation, and 4) temporal masking. Clinical measures of temporal ordering and temporal resolution are available; however, at this time, there are no clinically feasible measures of temporal integration or temporal masking. The most widely used clinical tests of temporal ordering are the Frequency Pattern Test (FPT) and the Duration Pattern Test (DPT) (Emanuel et al. 2011). Individuals with cerebral lesions demonstrate temporal ordering deficits (Belmont and Handler, 1971; Karaseva, 1972; Swisher and Hirsch, 1972; DeRenzi et al. 1977). Patients with compromise of the auditory areas of either hemisphere or of the

interhemispheric pathways present difficulties on the FPT and DPT (Musiek et al. 1980; Pinheiro and Musiek, 1985; Musiek and Pinheiro, 1987; Musiek et al. 1990; Musiek et al. 1994). These tests impose some degree of cognitive load in view of the complex response mode required; however, more recently developed tests for pitch and time sequence analysis hold promise for the assessment of these important facets of auditory processing (Grube et al. 2012; Grube et al. 2013).

Temporal resolution or discrimination refers to the shortest duration of time in which an individual can discriminate between two auditory signals (Gelfand, 1998). One of the most common measures of temporal resolution using behavioral methods is gap detection that requires subjects to indicate whenever they hear a "silent" interval embedded in an ongoing sound or noise burst. Two measures of gap detection are commonly used clinically—the Gaps-in-Noise (GIN) (Musiek et al. 2005) and the Random Gap Detection Test (RGDT) (Keith, 2002). Findings in these two tests are, however, dissociated in clinical populations and this has been attributed to a higher load on attention for the RGDT task compared to the GIN (Iliadou et al. 2014). The GIN appears to be more sensitive to cortical compromise than to brainstem involvement (Musiek et al. 2005). Several new clinically viable gap detection procedures have been introduced recently (Griffiths et al. 2001; Lister et al. 2006). One such procedure, the Adaptive Test of Temporal Resolution (ATTR), utilizes a computerized, adaptive psychophysical methodology to evaluate temporal resolution (Lister et al. 2006).

Monaural low-redundancy speech tests are among the oldest tests used to assess the CANS (Bocca et al. 1954; Bocca et al. 1955). These tests are administered monaurally using

stimuli that have been degraded electroacoustically or digitally in the frequency/spectral, temporal, or intensity domain (i.e., low-pass filtered speech (LPFS) tests, speech-in-noise (or speech-in-message competition) tests, and time-compressed speech tests). In addition to some degree of sensitivity to CANS lesions (i.e., moderately sensitive to brainstem and cortical dysfunction), they also provide insights regarding an individual's functional deficits (i.e., auditory closure and listening in noise), as well as one of the most common complaints of individuals seen for CAPD evaluation (i.e., understanding speech in background noise), and therefore, offer practical information for intervention (Bellis and Ferre, 1999; Bellis, 2003; Musiek and Baran, 2004). When a listener with reduced intrinsic redundancy (CANS dysfunction) listens to unaltered speech with normal extrinsic redundancy, normal speech recognition performance is still expected; however, when speech is degraded (i.e., extrinsic redundancy is reduced), listeners with reduced intrinsic redundancy (due to CANS dysfunction) show a significant deficit in speech recognition performance. Peripheral hearing loss, as well as CANS dysfunction, reduces the intrinsic redundancy of the auditory system. Peripheral hearing loss reduces the ability of the auditory system to resolve spectral detail; therefore, monaural low-redundancy tests are subject to the potential confound of peripheral hearing loss (Chermak and Musiek, 1997). Since all monaural-low redundancy tests are heavily dependent on resolution of rapid frequency-intensity interactions, the clinician should balance the value of these tests in the central auditory diagnostic battery against their potential to confound results. Results should be interpreted with caution when used as part of a central auditory test battery with individuals with known hearing loss (Baran and Musiek, 1999).

Given the relative insensitivity of the pure-tone audiogram to the function and integrity of the central auditory system, the authors recommend that audiologists consider including a screen

for central auditory function in their basic audiological evaluation. A screening measure is indicated when the patient's auditory complaints are inconsistent with the degree of deficit as represented by the pure-tone audiogram or when the patient's history raises the possibility of higher order auditory involvement. Unfortunately, research has lagged on the development of screening tests; however, dichotic digits and gap detection may be used for screening (as well as diagnostic purposes) since they pose minimal language and cognitive load and they are sensitive to dysfunction across the CANS (Hurley and Musiek, 1997; Musiek et al, 2005; Musiek, Chermak, Weihing, Zappulla, & Nagle, 2011). Obviously, other test might be appropriately used as screeners; however, only tests with established sensitivity to CANS involvement that can be administered to a relatively short period of time should be considered.

Auditory Evoked Potentials

Electrophysiologic potentials can be useful in the evaluation of the CANS. In addition to providing a more objective measure of the CANS, their mechanisms of generation can be more directly tied to their underlying anatomy and physiology (i.e., generator mechanisms) than possible with behavioral tests. A brief discussion follows of the auditory brainstem response (ABR), auditory middle latency responses (AMLR), the cortical auditory evoked response (P1-N1-P2), mismatch negativity (MMN), and the cognitive P300 response.

The ABR arises from the auditory brainstem nuclei and pathways. The ABR consists of five to seven peaks, with waves I and II recognized as the scalp-recorded 8^{th} nerve compound action potential. Waves III through V are indicative of activation of nuclei of the cochlear nucleus, superior olivary complex, lateral lemniscus, and the neural tracts connecting them. Wave III is associated with lower brainstem nuclei whereas waves IV-VII, and especially wave

V are associated with upper brainstem nuclei. The absence or abnormality of ABR peaks beyond waves I and II is indicative of brainstem lesions (See Musiek, Baran, Shinn, Guenette, Zaidan, & Weihing, 2007 for review).

The auditory middle latency response (AMLR) is generated by the auditory thalamus (medial geniculate body), the fiber tract (auditory radiation) to the cortex from thalamus, and the primary auditory cortex on Heschl's gyrus. Lesions of the primary auditory cortex will reduce or eliminate the AMLR. Cortical lesions of the temporal lobe result in abnormality or absence of the P1-N1-P2 complex (Knight et al. 1980; Bahls et al. 1988; Musiek and Baran, 2004; Musiek, Baran, Shinn, Guenette, Zaidan, & Weihing, 2007; Cavinato et al. 2012). The MMN is dependent upon the integrity of the auditory cortex at the supratemporal plane and/or lateral posterior temporal gyrus. The P300 has widespread generators and indicates activation of cortex associated with cognitive processes of attention, working and long-term memory, and perception. P300 may be present even after auditory cortex ablation (Harrison et al. 1986), suggesting that P300 may be used to assay auditory processing abilities, even when the auditory cortex has been extensively compromised.

Recording auditory evoked potentials (AEPs) in response to stimuli used in behavioral tests of central auditory function, as well as recording AEPs while subjects actually perform a central auditory test are promising hybrid approaches emerging in the diagnosis of CAPD. While the measurement of hearing thresholds using AEPs is common in clinics and labs worldwide, the recording of AEPs in response to more complex stimuli and/or while an individual concurrently performs a behavioral central auditory test has emerged recently as a potentially powerful

research and clinical tool. Jerger et al. (2002) demonstrated the potential of this procedure using gap detection and dichotic listening tasks with twins, one of whom was diagnosed with CAPD. Palmer and Musiek (2013) reported that amplitude of the N1-P2 late potential changed in response to changes in the duration of gaps presented in broadband noise, and that the N1 – P2 potential closely approximated behavioral gap detection thresholds in normal subjects. Other behavioral procedures also have been inserted into various AEP paradigms. For example, dichotic stimuli have been employed using mismatch negativity (MMN) to determine hemispheric advantages in dichotic listening (Yasin, 2007). The MMN also has been used to measure auditory discrimination, yielding impressive correlations with results obtained behaviorally (Pakarinen et al. 2007). The CANS of individuals who successfully perform the behavioral task and produce repeatable AEPs for a given auditory task must present high auditory integrity, reflecting both the integrity of the neural substrate underlying the behavioral task as well as the neural substrate of the pathways responsible for generating the AEP (Musiek, Chermak, and Cone-Wesson, in press).

Software to Develop Clinical Tests

As noted above, there are auditory functions for which we have limited tools or no commercially available tools to measure with documented sensitivity and specificity (e.g., sound localization, temporal integration, temporal masking). Clinicians with sufficient computer skills might use MatLab or Adobe Audition (formerly Adobe Cool Edit Pro) to develop measures of auditory skills. At a minimum, the clinician must obtain norms for these novel measures, and ultimately establish the measure's sensitivity and specificity if the measure is to be used for

clinical diagnosis (see Weihing and Atcherson, 2014 for discussion of clinical decision analysis). Sound Auditory Training, a soon to be released web-based toolkit to train auditory skills, also is designed to allow clinicians to assess a range of auditory skills using well-controlled stimuli in a game environment for children or in a more standard psychophysical paradigm for adults (Chermak, Weihing, and Musiek, in press).

IX. Summary

The pure tone audiogram has served and will continue to serve an important role in audiological evaluation. However, audiologists recognize the importance of assessing the central auditory system to fully evaluate auditory or hearing function. The purpose of this article was to elaborate this point, its rationale, and its implications. While recognizing the important role of the pure tone audiogram in clinical audiology, we reviewed data demonstrating the shortcomings of pure tone threshold testing in the broader context of assessing overall hearing status. We emphasized that the audiogram provides insight as to the sensitivity of the auditory system to simple stimuli, but that is of little value in providing information about other aspects of auditory function, such as supra-threshold processes, discrimination, temporal processes, binaural processes, and other complex acoustical processes. These limitations of the pure tone audiogram are particularly evident in individuals with central auditory disorders where commonly observed "normal findings" on a pure tone audiogram can be misleading if such findings are assumed to reflect the status of the entire auditory system, including central auditory structures and processes. Even in cases of cochlear and auditory nerve involvement, normal pure tone thresholds are surprisingly common, further revealing the shortcomings of this routine audiometric measure. Several unique studies were highlighted to demonstrate that audiograms do

not always reflect damage to the cochlea –a finding seemingly counterintuitive. A section was devoted to reports of various degrees of auditory symptoms and difficulties presented by individuals with normal pure tone audiograms, reflecting an important disassociation between the pure tone audiogram and patient complaints. Although seen in only a minority of cases, we discussed the finding of normal pure tone thresholds in those with auditory nerve involvement. We reviewed the initial impetus for testing beyond the audiogram ---- central auditory involvement--- and this perspectives piece concluded with a brief overview of available tests and procedures that assess the central auditory system, which in some instances also may provide insight into the function of the auditory periphery.

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