EFFECTS OF ADDING MONAURAL AND BINAURAL NOISE TO A DICHOTIC LISTENING TASK

by

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As members of the Audiology Doctoral Project Committee, we certify that we have read the Audiology Doctoral Project prepared by: Carrie Ann Moritz Clancy

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and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement for the Degree of Doctor of Audiology.

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Final approval and acceptance of this Audiology Doctoral Project is contingent upon the candidate's submission of the final copies of the Audiology Doctoral Project to the Graduate College.

I hereby certify that I have read this Audiology Doctoral Project prepared under my direction and recommend that it be accepted as fulfilling the Audiology Doctoral Project requirement.

Frank Musiek — Date: Apr 7, 2022
Speech, Language and hearing sciences

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DEDICATION

This work is dedicated to my husband, Joe, who provides for me in every way, and to our children, J.T. and Piper, who are my inspiration, always and in everything I do.

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ABSTRACT

The Dichotic Digits Test (DDT) evaluates central auditory nervous system (CANS) dysfunction. The DDT is widely used in audiology clinics worldwide, because it is clinically efficient and has good sensitivity and specificity for CANS lesions. However, the DDT shows a strong ceiling effect, which can mitigate its ability to detect subtle CANS dysfunction. This study examines the effects of adding monaural and binaural speech-spectrum noise to the DDT, in an effort to make the test more challenging to the CANS and thereby reduce the observed ceiling effect. Effects of monaural and binaural noise on different DDT scoring indices, including Individual Ear Percent Correct Scores, Combined Total Percent Correct Scores, and Dichotic Difference Scores, as well as noise effects on the Right Ear Advantage for speech, are investigated here. Statistically significant differences on all indices were found between monaural and binaural noise-added conditions, suggesting a possible advantage for binaural listening in noise. These preliminary findings suggest that adding noise to tests of dichotic listening and assessing dichotic listening patterns in noise could add sensitivity to evaluations of CANS integrity and function.

Keywords: binaural hearing, ceiling effect, central auditory processing, dichotic listening, neuroaudiology, Right Ear Advantage, speech-in-noise

INTRODUCTION

What is Central Auditory Processing?

The American Speech-Language-Hearing Association (ASHA) defines central auditory processing as "the perceptual processing of auditory information in the central auditory nervous system (CANS) and the neurobiological activity that underlies that processing and gives rise to electrophysiologic auditory potentials." The ASHA Practice Portal for Central Auditory Processing Disorder goes on to state that, "Knowledge of the neuroanatomy and physiology of the central auditory nervous system is essential for understanding and interpreting underlying processes" (ASHA, n.d.). From a basic anatomic point of view, central auditory processing occurs after sound stimulation is received by the peripheral auditory system, which includes the outer ear, middle ear, cochlea, and auditory nerve. Once sound is transmitted through the periphery, the central auditory nervous system (CANS) then conveys the auditory information from the root entry zone of the cochlear nucleus through the auditory brainstem pathway to the auditory cortex. From the auditory cortex, this information can be transmitted between the two hemispheres of the brain via the corpus callosum, or it can be conveyed to the frontal lobe for cognitive processing.

What is Dichotic Listening?

Dichotic listening is a central auditory process that involves listening with both ears. As opposed to diotic listening, which involves listening to the same stimulus presented simultaneously to both ears, and monotic listening, which involves a stimulus presented to only one ear, dichotic listening involves listening to different stimuli presented simultaneously to each ear. Dichotic listening can be further broken down into two separate processes, binaural integration and binaural separation. Binaural integration is a listener's ability to synthesize different acoustic information presented separately to each ear. Binaural separation is a listener's ability to isolate or segregate information from one ear or the other during a dichotic listening task (Weihing & Atcherson, 2014).

In most experimental dichotic listening paradigms, participants are asked to listen to dichotic stimuli and respond by verbal report. For example, in a binaural integration (or free recall) paradigm, listeners are asked to listen to dichotic stimuli and repeat back everything they hear in both ears. By contrast, in a binaural separation (or directed attention) paradigm, listeners are asked to repeat only stimuli heard in one ear or the other (Musiek & Weihing, 2011). As with behavioral tests of peripheral auditory sensitivity, response paradigms other than verbal report can be used, including hand raising, written responses, and picture pointing, but these may have different implications for interpretation of results.

Anatomic and Physiologic Mechanisms for Dichotic Listening

Studies of patients with confirmed neurologic lesions have provided insight into the neural mechanisms underlying dichotic listening. In a pair of studies published in 1961, Kimura examined dichotic listening in patients with temporal lobectomy and epilepsy, in order to assess the functional effects of damage to the auditory cortex (Kimura, 1961a; Kimura, 1961b). Her work, which has gained wide support and acceptance over the past 60 years, led to the proposal of the "structural" or "transmission line" model of dichotic listening, in which the majority of nerve fibers in the central auditory pathways leading from each ear cross over to the opposite side. This crossing over occurs in the low brainstem, beginning at the level of the stria of the cochlear nucleus. The majority of fibers are crossed by the time the pathway reaches the nuclei of the lateral lemniscus (Musiek & Baran, 2018). The crossed fiber pathways are referred to as the contralateral pathways, while the minority of fibers that do not cross over are referred to as the ipsilateral pathways. In dichotic listening, the ipsilateral pathways are suppressed, and the contralateral pathways become the primary route for auditory information to reach the auditory cortex (Westerhausen & Hugdahl, 2008).

In most adult listeners with normal hearing sensitivity, speech and language processing occurs predominantly in the left hemisphere of the brain, specifically in the posterior portion of the left superior temporal plane, including the primary auditory cortex, or Heschl's gyrus. Following the structural model outlined above, speech signals received in the right ear follow the dominant contralateral pathway, crossing over in the low brainstem and transmitting directly to the left auditory cortex for speech and language processing. Speech signals received in the left ear follow an analogous contralateral route to the right auditory cortex and from there are transmitted to the left auditory cortex via the corpus callosum, which is a prominent and heavily myelinated collection of axons connecting the left and right hemispheres of the brain (Musiek & Weihing, 2011).

According to Kimura's structural model, speech signals received in the right ear follow a relatively shorter pathway to the left auditory cortex and to the speech and language center in the left hemisphere, as compared to speech signals received in the left ear, which follow an indirect route to the same processing location (Kimura, 1961b). This anatomic mechanism leads to a functional effect known as the Right Ear Advantage (REA) for speech, whereby speech information received in the right ear is prioritized over speech information from the left ear in the course of normal auditory processing. The anatomic correlate of the REA was confirmed by Geschwind and Levitsky (1968), whose study of normal postmortem human brains found that the planum temporale, an auditory area immediately posterior to Heschl's gyrus, was significantly larger in the left hemispheres than in the right hemispheres. Later studies, including those by

Musiek & Reeves (1990) and Penhune et al. (1996) found that Heschl's gyrus itself is also larger in the left hemisphere than in the right, for normal adults. Together, these findings provide a strong anatomic underpinning for the relative importance of the left auditory cortex for speech and language processing.

Clinical Perspective

Tests of dichotic listening have been used for over 80 years to investigate normal function of the brain in response to the auditory stimulation. Stevens and Davis referred to the concept of "dichotic stimulation" in their classic 1938 book, *Hearing, Its Psychology and Physiology*. The paradigm of dichotic listening in research was devised by Broadbent and Ptacek, independently of one another, in the early 1950s (Broadbent, 1954; Ptacek, 1954). Tests of dichotic listening are commonly found in the psychology literature as well as in audiologic clinical and research contexts (Westerhausen, 2019). Current research in the field of speech, language, and hearing sciences has focused on using dichotic listening tests to examine learning difficulties in children, as well as to investigate "central presbycusis," or age-related changes to the CANS in adults (Weihing & Atcherson, 2014). A very recent study by Bhatt and Wang (2019) used the DDT to examine central auditory effects of past noise exposure in young women (age 18-35). These researchers found that standard DDT scores were significantly reduced and the REA less evident in young women with a history of high noise exposure, as compared to a control group with low noise exposure history.

Clinically, dichotic listening tests are used as part of a central auditory processing test battery to diagnose learning-based and/or neurologically-based central auditory processing disorder (CAPD) (Weihing & Atcherson, 2014). Well-known and commonly used dichotic listening tests include the DDT, Dichotic Rhymes, Staggered Spondaic Words (SSW), and

Competing Sentences (Emanuel et al., 2011). Dichotic listening tests have also been used in a variety of clinical situations outside the CAPD test battery. In the area of amplification and aural rehabilitation, central auditory tests of dichotic listening and temporal processing have been explored as potential measures of hearing aid benefit and satisfaction in patients with peripheral hearing loss (Davidson, 2020). In the area of hearing loss surveillance, a Digits in Noise (DIN) paradigm using both dichotic and diotic stimuli has been developed as a screening tool for peripheral hearing loss and has also been proposed as a method for distinguishing between conductive and sensorineural hearing losses in hard-to-reach populations (DeSousa et al., 2020a; DeSousa et al., 2020b).

The Dichotic Digits Test (DDT)

The DDT, as developed by Musiek (1983), is composed of naturally spoken recordings of the nine digits from 1 through 10 (excluding the digit 7, which has two syllables). Using a two-channel audiometer, differing pairs of digits are presented dichotically, one to each ear, at a comfortable suprathreshold hearing level (HL). The complete DDT consists of 40 presented dichotic digit pairs, for a total of 80 digits across both ears and 40 digits to each individual ear, right and left (Hurley & Musiek, 1997).

The DDT is used as part of a comprehensive CAPD test battery to evaluate central auditory nervous system (CANS) function. Specifically, the DDT is used to assess binaural integration, or a listener's ability to process different acoustic information presented simultaneously to each ear (Musiek, 1983). The DDT is an indicator of overall central auditory system function, as the binaural integration process involves the auditory brainstem and thalamocortical pathways, the auditory cortex, and transfer of information between the two hemispheres of the brain via the corpus callosum (Musiek, 1983).

The DDT has been used in clinics worldwide for over 30 years. A recent survey of practicing audiologists showed that over 50% of respondents reported using some type of dichotic listening test as part of their CANS assessment battery, with the DDT being among the most common (Emanuel et al., 2011). Additionally, the standard DDT has a reported 70-90% sensitivity and 80-90% specificity for CANS dysfunction (Weihing & Atcherson, 2014). However, the DDT demonstrates a strong ceiling effect, which is a measurement limitation occurring when the highest possible score on a test is achieved by a large number of participants, thereby decreasing the likelihood that the test has accurately measured the intended domain in the high scoring range (Austin & Brunner, 2003). With regard to the DDT, the ceiling effect only allows differentiation of performance in the moderate or low scoring range. For normal listeners, it can also obscure the typical REA for dichotic listening. These effects could potentially mitigate the diagnostic capability of the DDT in some clinical situations.

Motivation for Study

The primary objective in this study was to attempt to reduce the ceiling effect seen on the standard DDT in adult listeners with normal peripheral hearing. Typical DDT scores for adult listeners with normal peripheral hearing sensitivity are at or above 90% correct (Musiek, 1983). In this experiment, additional difficulty was introduced to the task by adding competing speech spectrum noise (SSN) to the presentation of the digit-pairs in the standard DDT.

Adding noise to an auditory task to increase its difficulty level is not a new idea. As far back as 1951, Miller, Heise, and Lichten experimented with speech intelligibility in noise by manipulating the type and context of the auditory stimulus. They found that digits, which are a small and closed stimulus set (like the one used in the DDT), reached 100% intelligibility at a signal to noise ratio (SNR) of -10 dB, while words in sentences required a +18 dB SNR for

100% intelligibility. For low-redundancy nonsense syllables, maximum performance reached only 70% at a +18 dB SNR (Miller, Heise, & Lichten, 1951).

The secondary objective of the present study was to evaluate the overall effects of competing noise on a dichotic listening task. It was hypothesized that adding speech spectrum noise to a commonly used behavioral dichotic listening task, in this case the DDT, would result in reduced performance due to the degraded signal quality of the stimuli in the noise-added conditions, which would lead to decreased redundancy and increased challenge in the CANS.

METHODS

Personnel

Testing was completed in the Auditory Research lab in the Department of Speech, Language, and Hearing Sciences at the University of Arizona, under the existing Institutional Review Board approval of the Neuroaudiology lab, Department of Speech, Language, and Hearing Sciences, University of Arizona. Testing was administered by Doctor of Audiology students from the Neuroaudiology lab, who had received training on the administration of the standard DDT and the protocols for the noise-added test lists.

Participants

Forty-three total participants (6 male, 37 female) were recruited for the study by convenience sampling between February 2019 and February 2020. (A sample recruitment flyer included in the Appendix.) The participant sample included students in the University of Arizona Department of Speech, Language, and Hearing Sciences; family and friends of student participants; and friends and acquaintances of the primary researcher. Participants were required to meet all of the following criteria for inclusion in the study.

1. Informed consent for testing.
2. Age 18-50 years.
3. Normal, bilaterally symmetric peripheral hearing sensitivity. (Please see Procedures, below, for further details.)
4. Self-report of English as primary spoken language.
5. No self-reported history of tinnitus, speech-language disorder, attention disorder, head trauma, or neurologic disorder.

Of the 43 total participants recruited and tested, 20 participants were included in the final data analysis. Collected demographic information indicated that the participant sample included one male (19 females), two left-handed individuals (18 right-handed), and 11 participants with self-reported musical background (9 with no music training).

For the participants not included in the final data set, reasons for exclusion and number of participants for each were as follows: history of speech or language disorder (1), history of attention disorder (1), history of head injury or neurologic disorder (5), persistent tinnitus (2), primary language other than English (2), failed pure tone hearing screening at one or more tested frequencies (1), and asymmetric SRTs (1). Some participants reported or experienced more than one exclusionary criterion. Additionally, 17 participants were withdrawn because they did not complete testing in all noise conditions.

Materials

Specialized testing materials were created using digital recordings of the standard DDT (Musiek, 1983) and Audacity® sound processing software (Audacity Team, 2019). In these digital recordings, onset and offset of the digit presentations in each set of paired lists were synchronized to occur within 70 msec across the two presentation channels, to ensure that dichotic perception was maintained (as described in Musiek, 1983). The standard DDT digit lists were then altered by adding speech spectrum noise at two different signal-to-noise ratios (SNRs) to one or both digit presentation tracks in each pair (for monaural and binaural noise, respectively). First, speech spectrum noise at equivalent RMS-amplitudes to the presentation of the digits (minus the intervening silences) was added, creating a 0 dB SNR (i.e., the digit presentations and the noise were equal in RMS-amplitude). The noise level in the 0 dB SNR tracks was then increased to create sets of otherwise identical tracks with either a -2 dB SNR or a -6 dB SNR. Noise and digit-presentation track files were combined into single-track presentations with noise onset/offset timed to occur one second before and after the presentation of the digits, and simultaneously across channels.

Testing was completed in a sound-attenuated booth (ECKEL Noise Control Technologies, model CL-14-LP MOD) in the Auditory Research lab at the University of Arizona. All stimuli, including spondees (CID W-1), standard DDT stimuli, and noise-added DDT stimuli were presented via an external CD player, routed through the speech circuit of a GSI AudioStar Pro two-channel audiometer, and conducted via E-A-RTONE 3A insert earphones. Calibration was performed using a Larson-Davis System 824 sound level meter and a Larson-Davis 2-cc artificial ear coupler at 70 dB SPL (A-weighted scale).

Study Design

Using a repeated measures study design, each participant was administered one DDT test list in standard form (no noise added) and DDT test lists with binaural, monaural right, and monaural left noise added. For each of the noise-added conditions, the lists were administered at two different noise levels, -2 dB SNR and -6 dB SNR. This resulted in a grand total of seven

DDT test lists per participant. The control (no noise) condition and the six noise-added conditions were presented in randomized order for each participant.

Procedure

Initial screening protocol for inclusion in the study included informed consent review, subject history questionnaire, and otoscopic examination. Participants then underwent bilateral pure tone screening (250-8000 Hz) at 25 dB HL and bilateral Speech Reception Threshold (SRT) testing using the Chaiklin et al. (1967) method to confirm normal peripheral hearing sensitivity and between-ear symmetry within 5 dB.

The following procedures were used for DDT testing, in accordance with standard DDT protocol defined in previous publications by Musiek (1983) and Musiek et al. (1991). Each DDT test list contained 20 digit-pairs presented dichotically to each ear, for a total of 40 digits per ear, or 80 digits in total. Presentation intensity level for all test lists was 50 dB SL (re: SRT), equalized between ears. Participants were given standardized instructions and were asked to complete three practice items before testing began. Clarification or reinstruction was provided after the practice items, if necessary. The participant response strategy for all DDT lists was free recall, meaning that digit order and ear designation were not specified. Participants were given as much time as they needed to respond and were instructed to guess if they were unsure of the digits. For each ear, the number of correctly reported digits was totaled and converted to a percentage score.

In the initial stages of the study, testing was completed over two sessions of about 30 minutes each. The test protocol and procedures became more streamlined over the course of the study (as described below, under Data Collection and Management), and later testing was completed in single sessions of 30-45 minutes each.

Data Collection and Management

Study data were initially collected using paper forms for informed consent, screening questionnaires, and test scoring. After the first round of testing, data collection and management were converted to electronic methods, using REDCap (Research Electronic Data Capture) software tools hosted at the University of Arizona. REDCap is described by its development team as “a secure, web-based software platform designed to support data capture for research studies, providing 1) an intuitive interface for validated data capture; 2) audit trails for tracking data manipulation and export procedures; 3) automated export procedures for seamless data downloads to common statistical packages; and 4) procedures for data integration and interoperability with external sources” (REDCap, n.d.). Specialized data collection forms were created in REDCap for demographic information, screening questionnaires, and DDT scoring in all seven noise conditions.

No personally-identifying information for any participant was included in the REDCap data collection for this project. Paper consent forms were stored in a secured file in the Auditory Research lab. Paper score sheets, when used, were de-identified and stored separately in a secured file in the Neuroaudiology lab. (Sample score sheets are included in the Appendix.)

Statistical Analysis

Statistical analysis was performed with support from Dr. Mark Borgstrom and Mohammad Torabi of the University of Arizona Information Technology Services department, using IBM SPSS Statistics (Version 27.0) predictive analytics software. Mixed model analyses of variance (ANOVAs) were used to examine the fixed effects of *noise condition* (no noise added, binaural noise added at -2 and -6 dB SNR, and monaural noise added for each ear at each

SNR), *ear* (either right or left), and the interaction of *ear by noise condition*, as well as to account for the random effect of individual participants (or *intercept*).

Dependent variables were the following DDT scoring indices: Individual Ear Percent Correct Score (either Right Ear or Left Ear), Combined Total Percent Correct Score, and Dichotic Difference Score (DDS). Individual Ear Percent Correct Score is defined here as the number of test items correct for the designated ear (Right or Left), divided by the total number of items for each ear (40), then multiplied by 100. Combined Total Percent Correct Score is defined as the sum of the Right Ear Percent Correct Score and the Left Ear Percent Correct Score, divided by two. Finally, DDS is defined as the Right Ear Percent Correct Score minus the Left Ear Percent Correct Score (as described in Weihing & Atcherson, 2014). The DDS can indicate both the degree of asymmetry between the ears and the direction of the asymmetry (i.e., which ear is stronger or weaker). A positive DDS would indicate a right ear advantage, while a negative DDS would indicate a left ear advantage and a DDS of zero would indicate binaural symmetry.

Table 1. Formulas for DDTN scoring indices.

DDTN Scoring Index	**Formula**
Individual Ear Percent Correct Score (RE = right ear, LE = left ear)	(# of RE items correct / 40) x 100 **or** (# of LE items correct / 40) x 100
Combined Total Percent Correct Score (RE = right ear, LE = left ear)	(RE Percent Correct Score + LE Percent Correct Score) / 2
Dichotic Difference Score (DDS)	RE Percent Correct Score – LE Percent Correct Score

RESULTS

Overall Effects

Significant overall effects of *intercept* were seen on Combined Total Percent Correct Scores ($F [1, 19] = 5201.311$, $p < 0.0001$) and Individual Ear Percent Correct Scores ($F [1, 19] =$

98.963, $p < 0.0001$). These effects indicate that Combined Total Percent Correct Scores and Individual Ear Percent Correct Scores varied significantly and systematically between individual participants. Significant *intercept* effects were not seen on DDS (F [1, 133] = 1.835, $p = 0.178$), suggesting that DDS did not vary significantly between participants.

Individual Ear Percent Correct Scores

Statistical analysis revealed a significant main effect of *noise condition* on Individual Ear Percent Correct Scores for both right (F [6, 247] = 184.369, $p < 0.0001$) and left (F [6, 247] = 177.880, $p < 0.0001$) ears. Individual Ear Percent Correct Scores for both ears declined systematically as the SNR was decreased (i.e., as the noise level was increased).

There was no significant effect of *ear* on Individual Ear Percent Correct Scores in the control condition (F [1, 247] = 0.135, $p = 0.714$). Without added noise, Individual Percent Correct Scores for right and left ears were not significantly different from one another. However, significant effects of *ear* were seen on Individual Ear Percent Correct Scores in the binaural -2 dB SNR condition (F [1, 247] = 4.258, $p = 0.040$) and in the binaural -6 dB SNR condition (F [1, 247] = 6.131, $p = 0.014$). Individual Ear Percent Correct Scores for both right and left ears declined systematically as binaural noise was increased (i.e., as SNR decreased). Additionally, Right and Left Ear Percent Correct Scores differed significantly from one another at both binaural SNRs.

As expected, significant *ear* effects were also seen in all four monaural noise conditions, due to the practical nature of presenting noise to only one ear. In the monaural noise conditions, both Right and Left Ear Percent Correct Scores declined systematically as ipsilateral noise was added (i.e., as SNR decreased), while scores for the ear opposite the noise did not change significantly when noise was added. Further analysis was performed regarding Individual Ear

Percent Correct Scores in ipsilateral noise (i.e., Right Ear Percent Correct Score in monaural right noise vs. Left Ear Percent Correct Score in monaural left noise) at both SNRs. In this analysis, there was no significant effect of *ear by noise condition* on Individual Ear Percent Correct Scores at either the -2 dB SNR (F [1,19] = 1.347, p = 0.260) or the -6 dB SNR (F [1,19] = 0.167, p = 0.687). Right and Left Ear Percent Correct Scores in ipsilateral noise at the same SNR were not significantly different from one another.

Combined Total Percent Correct Scores

Statistical analysis showed a significant main effect of *noise condition* on Combined Total Percent Correct Scores (F [6, 247] = 88.070, p < 0.0001). Combined Total Percent Correct Scores declined systematically as noise was added (i.e., as SNR decreased). As expected, there was no significant effect of *ear* on Combined Total Percent Correct Scores (F [1, 247] = 2.120, p = 0.147), because this index is, by definition, an average of each participant's two Individual Ear Percent Correct Scores in each noise condition.

Dichotic Difference Scores

Statistical analysis revealed a significant main effect of *noise condition* on DDS (F [6, 133] = 237.339, p < 0.0001). While DDS was not significantly affected by the addition of binaural noise, DDS scores did increase systematically and significantly as monaural noise was added (i.e., as SNR decreased, in the monaural noise conditions only). This result indicates a greater degree of asymmetry between the two ears in the monaural noise conditions, which would be expected when presenting noise to only one ear. As with the Combined Total Percent Correct Score, effects of *ear* were not considered for DDS, because by definition, the DDS is the difference between each participant's two Individual Ear Percent Correct Scores.

Control (No Noise) Condition

In the control condition, Individual Ear Percent Correct Scores for both ears and Combined Total Percent Correct Scores were generally consistent with previously published results for normal hearing adult listeners on the standard DDT (Musiek, 1983), as shown in Table 2. Combined Total Percent Correct Scores and Dichotic Difference Scores were not specifically reported in Musiek (1983), and norms for these scoring indices have not been established (Weihing & Atcherson, 2014). For the present study, pairwise comparison of means revealed that Right Ear and Left Ear Percent Correct Scores were not significantly different from one another in the control condition (p = 0.714).

Table 2. Comparison of present study control condition data with published DDT norms.

DDTN Scoring Index	**Published Norms [Musiek, 1983]** Mean (σ)	**Present Study** Mean (σ)
Right Ear Percent Correct Score	97.8 (2.9)	99.75 (0.77)
Left Ear Percent Correct Score	96.5 (1.7)	98.75 (1.90)
Normative criterion (2 σ below mean)	90% or greater for each ear	95% or greater for each ear
Combined Total Percent Correct Score	97.15* (not reported)	99.25 (1.03)
Dichotic Difference Score (DDS)	1.3* (not reported)	1.0 (2.05)

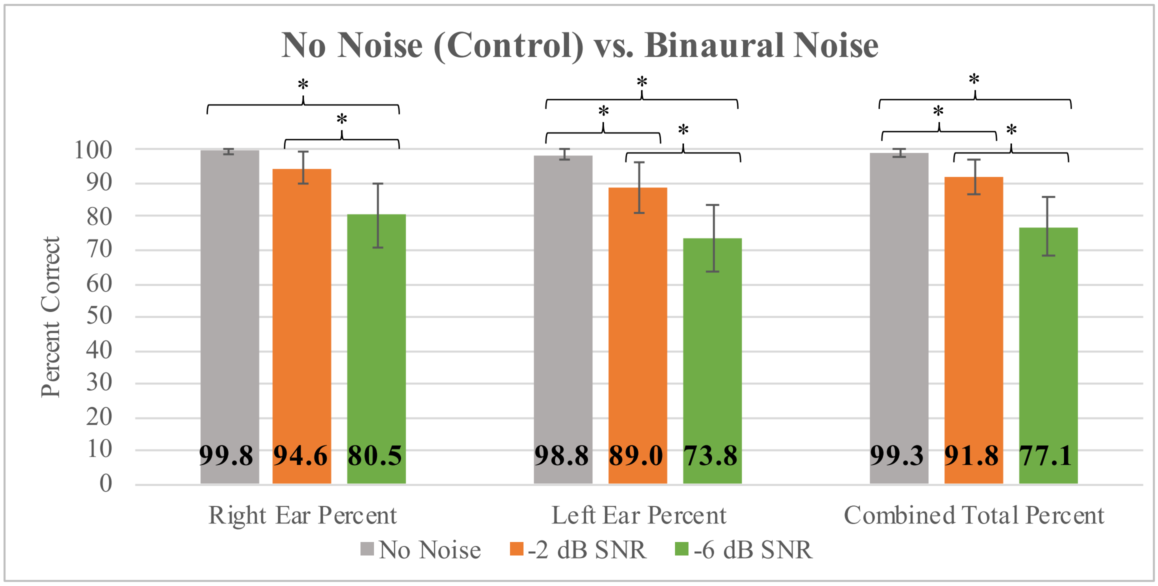
** Not reported in Musiek (1983); calculated from reported Right and Left Ear mean scores.*

Binaural Noise Condition

In the binaural noise condition, there was a systematic and statistically significant decrease in Individual Ear Percent Correct Scores for both ears and in Combined Total Percent Correct Scores as the SNR decreased (i.e., as the noise level increased), as shown in Figure 1. Of note, the mean difference between Right Ear Percent Correct Scores in the control and Binaural -

2 dB SNR conditions was not statistically significant ($p = 0.061$), but the mean Left Ear Percent Correct Scores between the same two conditions were significantly different ($p < 0.0001$).

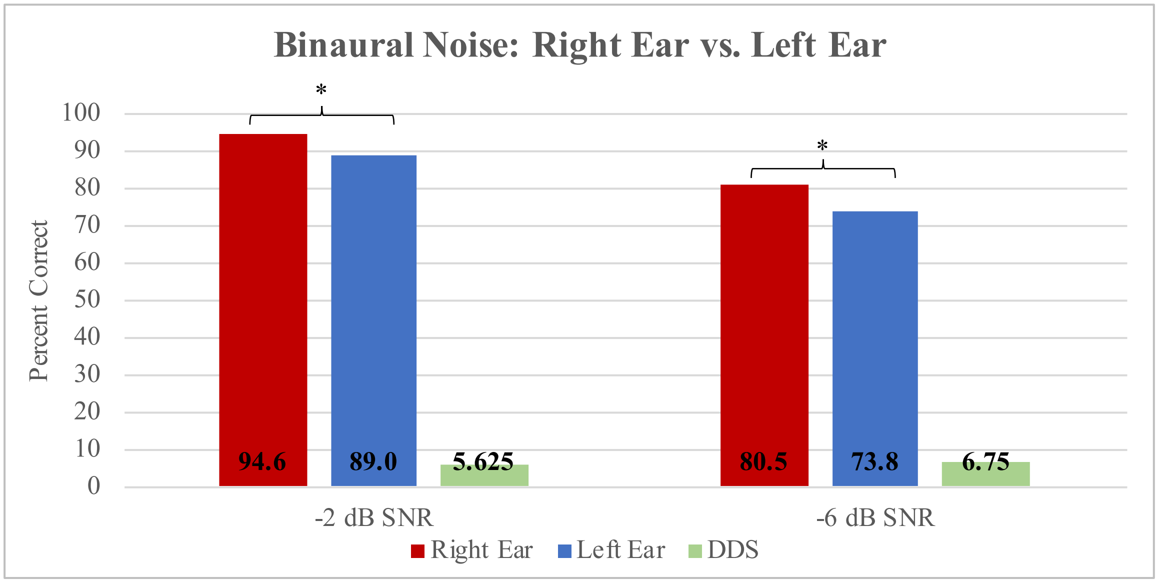
Figure 1. Control vs. Binaural Noise.



** indicates significance at p < 0.05.*

Pairwise comparisons revealed statistically significant differences between mean Right and Left Ear Percent Correct Scores at both the -2 dB SNR ($p = 0.040$) and the -6 dB SNR ($p = 0.014$), as shown in Figure 2. Mean Combined Total Percent Correct Scores were significantly different between the control and binaural -2 dB SNR conditions, between the control and binaural -6 dB SNR conditions, and between the binaural -2 dB SNR and binaural -6 dB SNR conditions ($p < 0.0001$, se = 1.928). However, mean DDS differences were not statistically significant between the control and binaural -2 dB SNR conditions ($p = 0.266$), between the control and binaural -6 dB SNR conditions ($p = 0.168$), or between the binaural -2 dB SNR and binaural -6 dB SNR conditions ($p = 0.786$).

Figure 2. Right Ear vs. Left Ear in Binaural Noise.

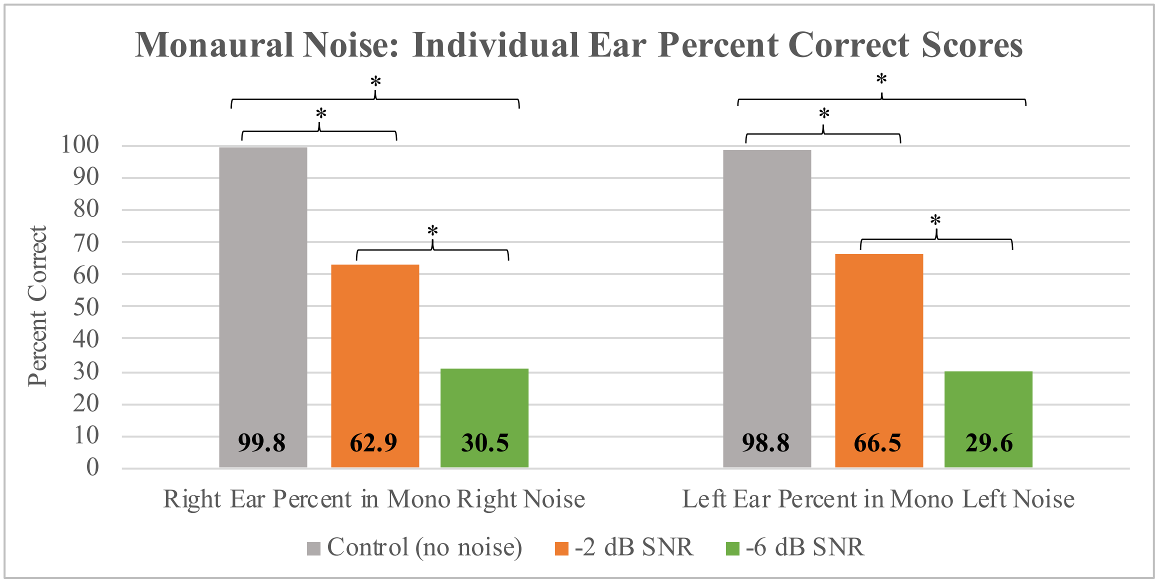


** indicates significance at $p < 0.05$.*

Monaural Noise Conditions

In the monaural noise conditions, as the SNR decreased (i.e., as the noise level increased), there was a systematic, statistically significant decrease in Individual Ear Percent Correct Scores for the ear with ipsilateral noise (shown in Figure 3). For the ear opposite the noise, there was no statistically significant change in Individual Ear Percent Correct Scores as compared with the control condition. There was also a systematic, significantly significant decrease in Combined Total Percent Correct Scores (shown in Figure 5).

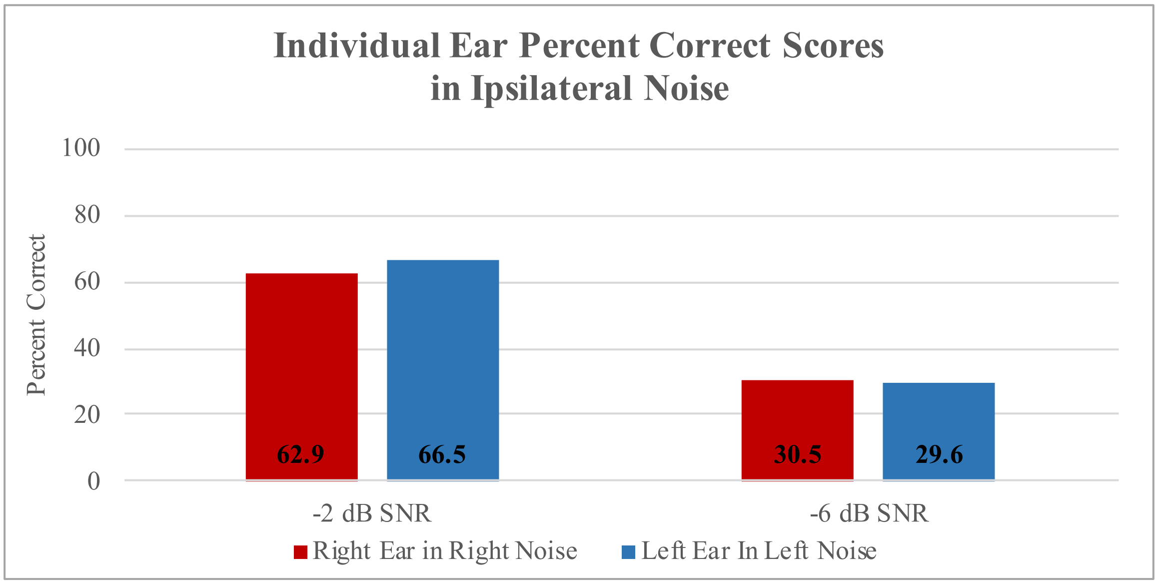
Figure 3. Individual Ear Percent Correct Scores in Monaural Noise.



* *indicates significance at p < 0.05.*

Pairwise comparisons of mean Individual Ear Percent Correct Scores in ipsilateral noise (i.e., Right Ear Percent Correct Score in monaural right noise vs. Left Ear Percent Correct Score in monaural left noise) are shown in Figure 4. While mean Individual Ear Percent Correct Score differences were statistically significant between the -2 dB SNR and the -6 dB SNR for both ears, the comparisons revealed no statistically significant differences between Right Ear Percent Correct Scores and Left Ear Percent Correct Scores in ipsilateral noise at either the -2 dB SNR (p = 0.26, se = 3.123) or at the -6 dB SNR (p = 0.687, se = 2.140).

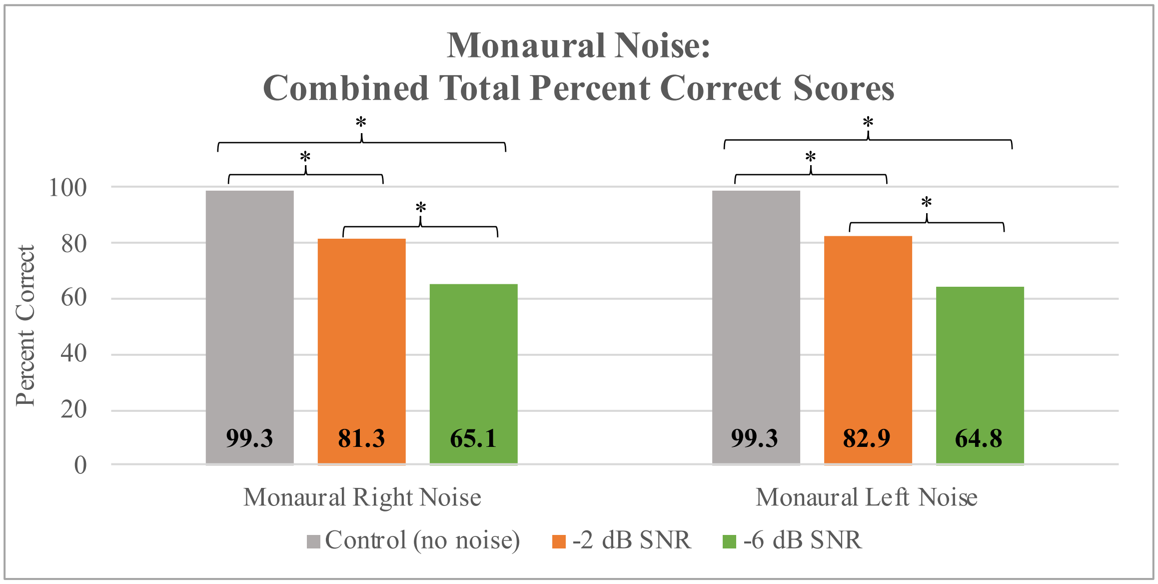
Figure 4. Individual Ear Percent Correct Scores in Ipsilateral Noise.



Between ear comparisons were not significant at p < 0.05.

Pairwise comparisons for mean Combined Total Percent Correct Scores (shown in Figure 5) revealed statistically significant differences between the control and monaural right -2 dB SNR conditions, between the control and monaural left -2 dB SNR conditions, between the control and monaural right -6 dB SNR conditions, and between the control and monaural left -6 dB SNR conditions ($p < 0.0001$, se = 1.928). Mean differences were also statistically significant between monaural right -2 dB SNR and monaural right -6 dB SNR, and between monaural left -2 dB SNR and monaural left -6 dB SNR ($p < 0.0001$, se = 1.928). No statistically significant differences in mean Combined Total Percent Correct Scores were found between monaural right and monaural left noise conditions at the -2 dB SNR ($p = 0.382$, se = 1.928) or at the -6 dB SNR ($p = 0.846$, se = 1.928).

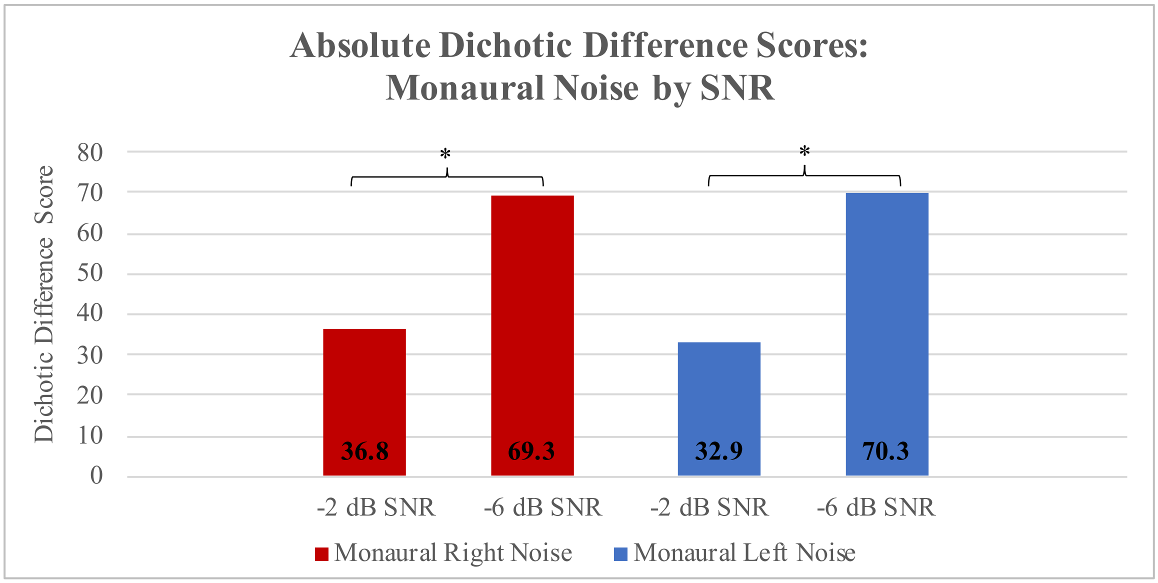
Figure 5. Combined Total Percent Correct Scores in Monaural Noise.



** indicates significance at $p < 0.05$. Pairwise comparisons between Monaural Right and Monaural Left Noise at each SNR were not significant at $p < 0.05$.*

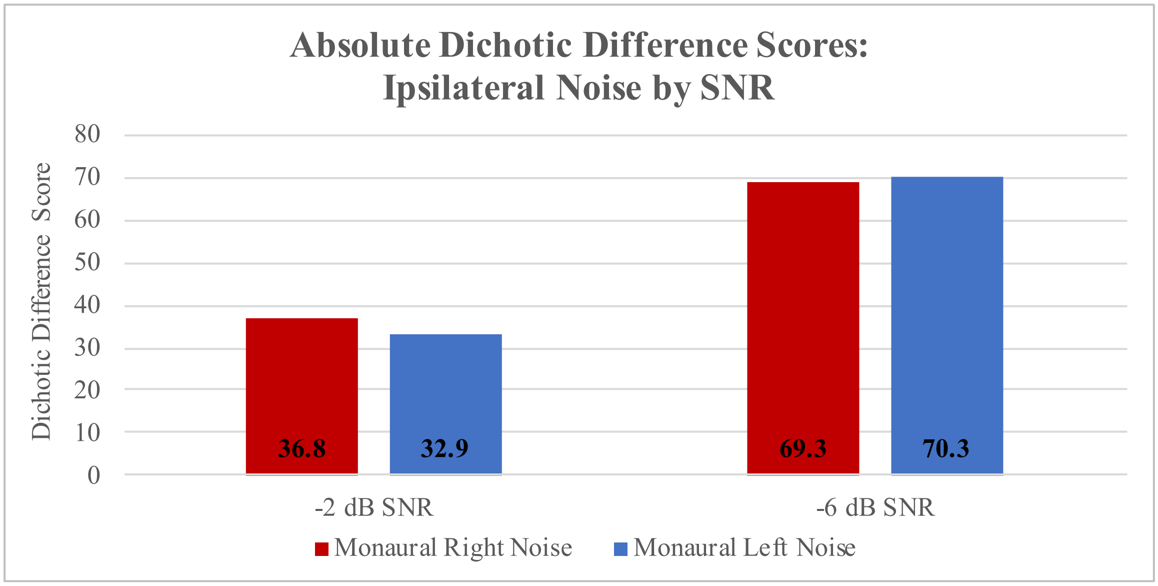
Recall that DDS can be measured as either a positive or negative value, in order to indicate both the degree and the direction of asymmetry between right and left ears. In the monaural right noise condition, results at both SNRs revealed expected negative DDS values, indicating stronger left ear performance. Conversely, in the monaural left noise condition, results revealed positive DDS values at both SNRs, as expected, indicating stronger right ear performance. In order to accurately compare the magnitudes of the mean DDS differences in the monaural noise conditions, pairwise comparisons were made using the absolute values of the DDS. Mean DDS differences were statistically significant between the control condition and all monaural noise conditions, due to the practical nature of presenting noise to only one ear ($p < 0.0001$, se = 3.305). Mean DDS differences were also statistically significant between the monaural -2 dB SNR and monaural -6 dB SNR conditions for both ears, as shown in Figure 6. However, as shown in Figure 7, mean DDS differences were not statistically significant between monaural right and monaural left noise conditions at the -2 dB SNR (p = 0.244, se = 3.305) or at the -6 dB SNR (p = 0.763, se = 3.305).

Figure 6. Dichotic Difference Scores in Monaural Noise by SNR.



** indicates significance at $p < 0.05$.*

Figure 7. Dichotic Difference Scores in Ipsilateral Noise by SNR.

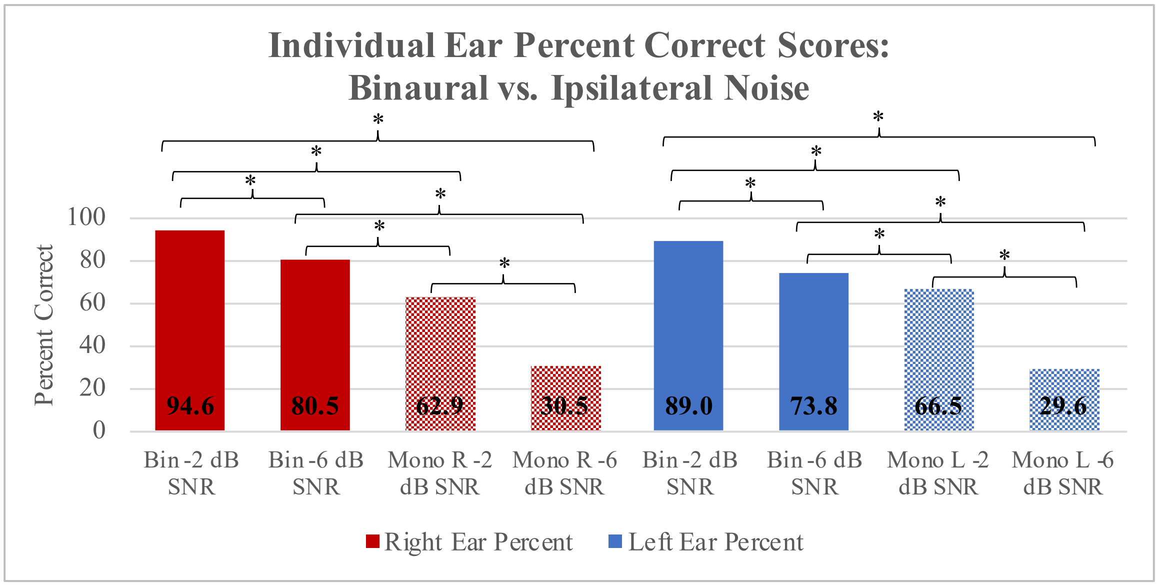


Pairwise comparisons between Monaural Right and Monaural Left Noise were not significant at $p < 0.05$.

Binaural vs. Monaural Noise Conditions

Analysis of Individual Ear Percent Correct Scores in binaural and ipsilateral monaural noise revealed significant mean differences between binaural and ipsilateral noise condition scores in all pairwise comparisons. Right Ear Percent Correct Scores differed significantly between binaural and monaural right noise conditions at the -2 dB SNR and the -6 dB SNR (F [6, 247] = 184.369, $p < 0.0001$). Likewise, Left Ear Percent Correct Scores also differed significantly between binaural and monaural left noise conditions at both SNRs (F [6, 247] = 177.880, $p < 0.0001$). As shown in Figure 8, Individual Ear Percent Correct Scores for both ears were significantly better in binaural noise conditions than in ipsilateral noise at the same SNR.

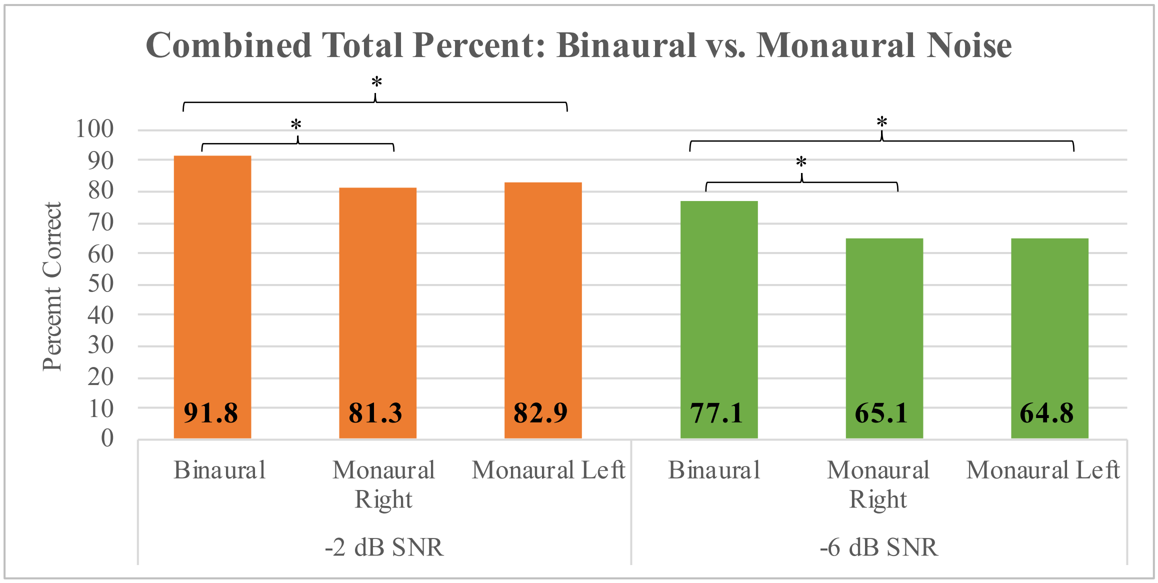
Figure 8. Individual Ear Percent Correct Scores: Binaural vs. Ipsilateral Noise



** indicates significance at p < 0.05. Between ear comparisons were not significant at p < 0.05.*

Analysis of Combined Total Percent Correct Scores in binaural and monaural noise conditions revealed significant mean differences between binaural and monaural noise conditions in all pairwise comparisons (F [6, 247] = 88.070, $p < 0.0001$). As shown in Figure 9, Combined Total Percent Correct Scores at both the -2 dB and -6 dB SNRs were significantly higher in binaural noise than in monaural noise in either ear at the same SNR level. Mean Combined Total Percent Correct Scores were not significantly different between monaural right and monaural left noise conditions at either SNR.

Figure 9. Combined Total Percent Correct in Binaural vs. Monaural Noise



** indicates significance at p < 0.05.*

DISCUSSION

Though not related to the primary objective, the most intriguing finding of the present study was the significant difference between the effects of binaural and monaural noise on dichotic listening, specifically the finding that both Individual Ear Percent Correct Scores and Combined Total Percent Correct Scores on the DDT were significantly higher in binaural noise than in monaural noise conditions. The comparisons shown in Figure 8 and Figure 9 above indicate a marked advantage for binaural listening in noise. Participants showed higher performance on this dichotic listening task when noise at either SNR was presented binaurally rather than monaurally in either ear. Furthermore, this study revealed a possibly enhanced REA for listening in binaural noise, as evidenced by significantly better right ear performance in binaural noise at both SNRs. Notably, this REA was not observed in the control condition or in any of the ipsilateral monaural noise conditions.

This finding is partially contradicted by the relative stability of the DDS in the binaural noise conditions. While Individual Ear Percent Correct Scores and Combined Total Percent Correct Scores were significantly affected by added binaural noise, the DDS scores were not significantly different between control and binaural noise conditions at either SNR. This indicates that listening symmetry between the two ears is maintained in binaural noise. However, despite the lack of statistical significance in this measure, mean DDS did increase as binaural noise was increased. (Please see Musiek, 2018 for further review of the interpretive value of the DDS.)

Overall, the finding of increased performance in the binaural noise conditions supports the idea that binaural hearing is advantageous over monaural hearing (Moore, 1991). Additionally, recall that in the present study, the noise in the binaural condition was diotic, or identical in phase and intensity for each ear. A recent study of speech intelligibility in diotic and dichotic noise conditions by Shabtai et al. (2017) reported a similar finding regarding diotic noise. These researchers tested speech-in-noise perception under four different target-noise conditions: (1) diotic target in diotic noise, (2) dichotic target in diotic noise, (3) diotic target in dichotic noise, and (4) dichotic target in dichotic noise. They found that speech-in-noise perception, as measured by SRT, was significantly improved in a condition similar to the binaural noise condition in the present study, where the target speech was dichotic and the competing noise was diotic. They also found that spatial release from masking in this condition was significantly greater than in the opposite (diotic target in dichotic noise) condition. Finally, the authors speculated that the mechanism behind these findings might relate to the precedence effect, where the auditory system could use interaural timing and intensity cues to separate the variable speech signal from the continuous background noise. It would be reasonable to apply the same theoretical mechanism to the binaural (diotic) noise condition in the present study.

The primary objective of this study was to reduce the ceiling effect observed in the standard DDT by adding binaural or monaural noise. This objective was effectively achieved by adding binaural noise, as evidenced by the systematic reductions in Individual Ear Percent Correct Scores for both ears, and by the systematic reduction in Combined Total Percent Correct Scores as binaural noise was increased. In the monaural noise conditions, the ceiling effect was reduced in the ear ipsilateral to the added noise, as evidenced by the systematic reduction in Individual Ear Percent Correct Scores for both ears as ipsilateral noise was added. Additionally, Combined Total Percent Correct Scores were also systematically reduced with the addition of monaural noise.

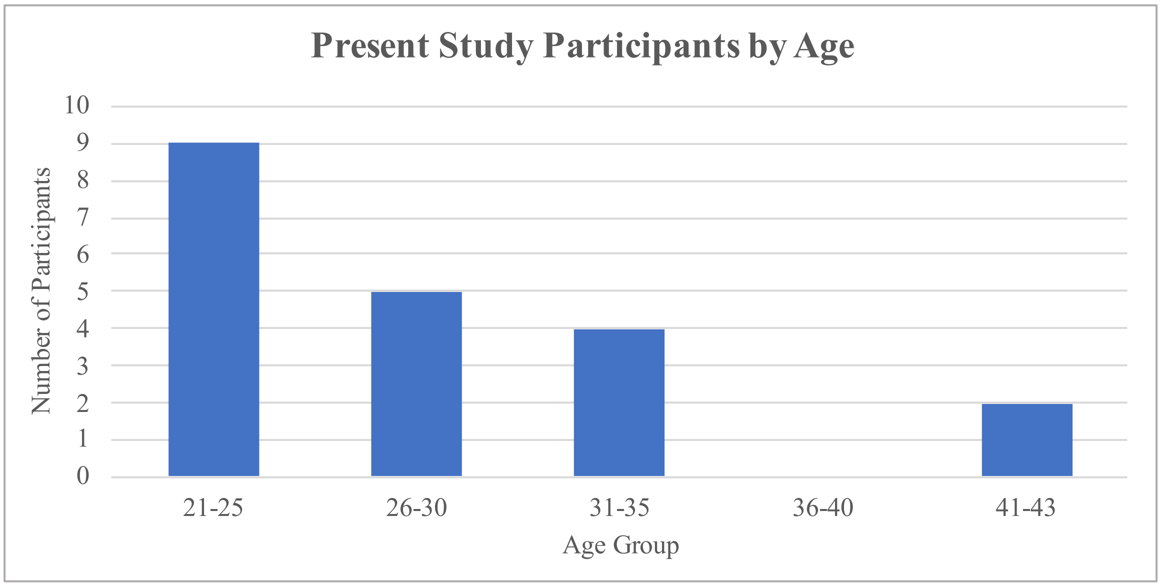
In contrast, Individual Ear Percent Correct Scores for the ear opposite the monaural noise were not observed to be significantly different from Individual Ear Percent Correct Scores in the control (no noise) condition. This result is a possibly a persistent reflection of the ceiling effect seen on the standard DDT. Because control condition scores were already at or near maximum performance, improvements or slight reductions would be difficult or impossible to observe. However, there is reason to believe that performance should have been decreased in the ear contralateral to the presented noise. After extensive psychophysical experimentation, Zwislocki (1972) presented a theory of "central masking," whereby a 3-18 dB threshold shift occurs for pure tone stimuli when low-intensity masking (below the intensity level of the acoustic reflex and the interaural crossover point) is presented to the contralateral ear. Mills, Dubno, and He (1996) replicated Zwislocki's findings using more sophisticated and varied psychophysical methods. They concluded that central masking is likely "indicative of sensory function rather than observer bias and fluctuations in observer criteria” (Mills et al., 1996, p. 3338). The present study did not find evidence of central masking in the contralateral ear for the monaural noise conditions; however, the ceiling effect in the control condition may well have obscured the significance of this effect.

The secondary objective of this study was to observe and evaluate the effects of competing noise on a dichotic listening task. At the beginning of this project, few reports on dichotic listening in noise were available in the literature. One notable study by Sequeira and colleagues (2008) investigated dichotic listening performance on consonant-vowel syllables (CVs) in two types of background noise, “traffic” and “babble,” which were considered to be representative of common environmental noise. These researchers found that while a significant REA was present in all conditions, the REA was significantly reduced in both the “traffic” and “babble” conditions. The contrasting findings of the present study, which show an enhanced REA in binaural speech spectrum noise, suggest the need for further investigation into the effects of different types of noise maskers at different intensity levels on dichotic listening performance.

Differences between the participant sample in the present study and the Musiek (1983) sample of normal hearing listeners may account for the differences between our control condition findings and the published norms from Musiek (1983). First, the Musiek (1983) sample of normal listeners included 45 adults ranging in age from 19 to 35 years and comprising “a wide range of vocational and educational backgrounds,” including “college students, nurses, technicians, general hospital personnel, and general outside laborers” (Musiek 1983, p. 80). The participant sample for the present study was smaller but similar in age range, comprising 20 adults from 21 to 43 years old, but heavily skewed toward the younger end (see Figure 10 below). This is an important similarity between the two participant groups, as Wilson and Jaffe

(1996) found that dichotic digit recognition performance varies significantly by age, with listeners under the age of 30 performing significantly better than listeners over the age of 60.

Figure 10. Present Study Participants by Age.



Perhaps more importantly, the criteria for defining normal hearing listeners were slightly different between the Musiek (1983) study and the present study. In Musiek (1983), participants had measured pure tone thresholds of less than or equal to 25 dB HL for octave frequencies 250-4000 Hz and speech discrimination ability of “90% or better bilaterally using the NU 6 test presented at a 30 dB SL (re: spondee threshold)” (Musiek 1983, p. 80). In the present study, inclusion criteria included passing a pure tone screening in both ears at 25 dB HL for all tested frequencies 250-8000 Hz, including the interoctave frequencies at 3000 and 6000 Hz. Additionally, the present study required participants to have SRTs of less than 30 dB HL in each ear and SRT symmetry within 5 dB between the two ears. These criteria are similar to, but not exactly the same as, the criteria suggested by Westerhausen (2019). Because the inclusion criteria used in the present study were somewhat more stringent than those used in the Musiek (1983) study, the present study's slightly higher control condition scores were not unexpected.

Regarding the aforementioned finding of no statistically significant REA in the present study's control condition, it is possible that our mixed model statistical analysis may have obscured this effect. A separate repeated measures ANOVA on the same data set did reveal a statistically significant difference between Right and Left Ear Percent Correct Scores in the control condition ($p = 0.042$). However, the primary researcher chose to continue with mixed-effects modeling for the statistical analysis in this study for several reasons. First, the final participant sample was smaller than anticipated ($n = 20$). Second, recalling that the standard DDT shows a strong ceiling effect, it was known beforehand that control condition data would not be normally distributed. Finally, some of the within-subjects data (for example, Right Ear and Left Ear Percent Correct Scores for the same participant) were not independent. For these reasons, using a simpler analysis model might have resulted in less accurate estimates. Gordon (2019) describes the advantages of using mixed-effects modeling in speech, language and hearing sciences research, specifically for small participant samples and samples with high individual variability or skewed distributions. One of the key advantages for mixed-effects modeling in the present study was the ability to include a random intercept for individual participant effects, which can reduce both Type I and Type II reporting errors in samples like the one in the present study, with considerable systematic variability among individual participants (Gordon, 2019).

The present study also collected demographic information about participants' self-reported hand dominance and past musical training. Hand dominance is an important indicator of speech and language laterality in the brain, with right-handed adults being more likely to demonstrate left hemisphere speech dominance, and thus the expected REA for speech, than left-handed adults (Bryden, 1970). Musicians, or people with musical training, have been shown to display a left ear advantage, or right hemisphere dominance, for nonverbal dichotic materials such as musical chords (Bever & Chiarello, 1974). However, Nelson et al. (2003) found no group differences between musicians and non-musicians for dichotic digit presentations such as those used in the present study paradigm.

Study Limitations

Data collection for this study was halted in March 2020, at the beginning of the global SARS-CoV-2 pandemic. Because recruitment of participants could not continue, the participant study sample was necessarily limited. The final study sample was small and heavily skewed toward young people and females. For this reason, analysis of the effects of demographic factors such as participant age, sex, hand dominance, and musical background was also deferred. Further investigation of acoustic and attention effects on the present paradigm was initially planned but ultimately could not be completed in the given timeframe for this project (please see Future Directions, below).

Another potential limitation of the present study is that the participant sample was predominantly female. While Hiscock and MacKay (1985) reported no significant differences in ear asymmetry in dichotic listening between men and women, Golding et al. (2006) and Fischer et al. (2017) found that females generally perform better than males on dichotic listening tasks. A recent meta-analysis of dichotic listening studies by Voyer (2011) suggested that men are slightly but significantly more lateralized than women on dichotic listening tasks, meaning that in general, men might display a more prominent REA. Because the present study sample was made up almost exclusively of women, the finding of no significant *ear* effect in the control (no noise) condition may have been affected by the unequal sampling of male participants.

Future Directions

The results of the present study suggest two specific avenues for further investigation. First, these results warrant exploration of the suggested binaural advantage for dichotic listening in noise. In the present test protocol, the speech spectrum noise presented in the binaural noise conditions was diotic, meaning that it was identical in each channel and interaurally in-phase. This interaural correlation of the added noise suggests a possible spatial release from masking effect in relation to the dichotically presented digits. A future study could adjust the binaural noise-added tracks to present interaurally uncorrelated noise to both ears simultaneously, so that the digit presentations and the speech spectrum noise are both dichotic. These results could be compared to the results of the present study to determine or confirm the effects of spatial release from masking in normal hearing listeners.

Second, the results from the monaural noise conditions in this study invite questions about the effects of attention on the current dichotic listening in noise paradigm. It is interesting to note that Broadbent first used the dichotic stimulus procedure in 1954, specifically to examine attention-related aspects of listening. More recent studies by Söderlund, Sikström, and Smart (2007), Sikström and Söderlund (2007), and Baijot et al. (2016) have found that adding moderate levels of noise to tasks in auditory, visual, or tactile modalities can increase target stimulus detection and attention in patients with Attention Deficit/Hyperactivity Disorder, (ADHD), through a phenomenon called stochastic resonance. In this phenomenon, the intensity of a target signal can be increased, relative to its detection threshold, by the addition of an optimal amount of background noise, which then influences the SNR (Sikström and Söderlund, 2007). This phenomenon could partially explain the present study's finding of better-than-expected dichotic listening performance in binaural noise. However, it does not fully clarify the findings of differentiated performance between binaural and monaural noise-added conditions.

The test protocol used in the present study employed a free recall (binaural integration) approach, where the listener was instructed to repeat all digits heard in both ears, in no particular order. Based on the markedly low Individual Ear Percent Correct Scores observed in the monaural noise-added conditions, it could be hypothesized that monaural noise, particularly at high levels, might produce a kind of "noise avoidance" effect, where the listener unconsciously attends to the ear with no noise added. However, the findings of an enhanced right ear advantage in binaural noise and the marked differences between binaural and monaural noise conditions suggest a possibly diminished role for attention and an increased influence of sensory processes in dichotic listening.

Effects of attention on dichotic listening could be explored further by presenting the control and noise-added conditions in a directed attention (binaural separation) paradigm, where the listener is asked to report only digits heard in in the specified ear, either right or left, with or without noise. Specifically, this line of study could compare scores for each of the noise conditions in the free recall paradigm used here to analogous scores in the proposed directed-attention protocols, in order to directly measure effects of attention on dichotic listening in noise.

SUMMARY

The preliminary findings outlined in this study show that adding monaural or binaural noise to the standard DDT can effectively reduce the ceiling effect observed on this test, potentially increasing the sensitivity and specificity of the test to CANS disorders by allowing interaural or hemispheric asymmetries to be more easily observed. Adding noise to the DDT increases the difficulty of the dichotic listening task without changing the instructions or requiring a novel type of response from the patient. Importantly, the noise-added DDT remains short and easy to administer, like its standard counterpart.

The key finding of the present study is the significant difference between the effects of binaural and monaural noise, specifically the unexpected finding of significantly better dichotic listening performance in binaural noise as compared to monaural noise. Emerging data from this study and others like it could add detail and precision to clinical interpretations of neural mechanisms underlying auditory processing dysfunction. Examining and establishing typical patterns of dichotic listening in noise for listeners with normal hearing sensitivity and normal central auditory processing could help to identify potential differences and atypical patterns in listeners with peripheral hearing loss and/or central auditory processing disorders. Overall, the results of this study suggest that further investigation of the interactions among dichotic listening, speech-in-noise perception, and attention could lead to development of a more sensitive and specific auditory processing test battery. However, further theoretical constructs await future data and analysis.

APPENDIX

Appendix 1. DDTN recruitment flyer.

The Dichotic Digit Test in Noise

The University of Arizona Neuroaudiology Lab is looking for participants for an experiment regarding auditory processing, specifically dichotic listening and binaural integration. The Dichotic Digit Test involves listening to a set of 4 digits (2 in each ear) and repeating them back as you hear them.

WHO: We are looking for **adults, 18-50 years old, with normal hearing.** Additionally, participants should be English-speaking and have no history of speech/language disorder, attention disorder, learning disability, or neurologic injury.

WHAT: This experiment will involve a screening questionnaire, hearing screening with pure tones and speech, and 4 lists of dichotic digits. The testing will take approximately 45-60 minutes.

WHEN: July and August. Flexible dates and times—whatever works with your schedule!

WHERE: U of A Speech, Language, and Hearing Sciences Building, 1131 E 2nd St, Room 315. Testing will take place in a sound booth, using insert earphones.

WHY: Because science!

To participate, or if you have questions,
please contact Carrie Clancy by email at
carrieclancy@email.arizona.edu.

Appendix 2. Sample DDTN participant history questionnaire.

Participant ID#: _______________ Date: ____________

Research Participant Questionnaire

Age: ______

Gender/Sex: __________

1. Do you have a known hearing loss? YES NO

2. Does your hearing ability fluctuate? YES NO

3. When did you first notice hearing difficulty? ___________________________

4. Is English your primary language? YES NO

5. Do you have any history of speech or language disorders? YES NO

6. Do you have any history of attention disorders? YES NO

7. Do you have any history of head injury or neurological disorder? YES NO

   If yes, please explain: ____

   ____

8. Do you have persistent tinnitus? YES NO

   If yes, is it in the RIGHT EAR, LEFT EAR, or BOTH? _________________________

9. Do you have any musical background? Yes No

   If yes, please explain: ____

   ____

10. Are you right or left handed? RIGHT LEFT

11. Would you like to be contacted to participate in future research? YES NO

12. Additional Comments: ____

____

____

____

Appendix 3. Sample DDTN scoresheet (original).

EXTENDED DICHOTIC DIGIT TEST [Frank Musiek, Ph.D.]
Dichotic Digits in Noise, 22 Feb 2019

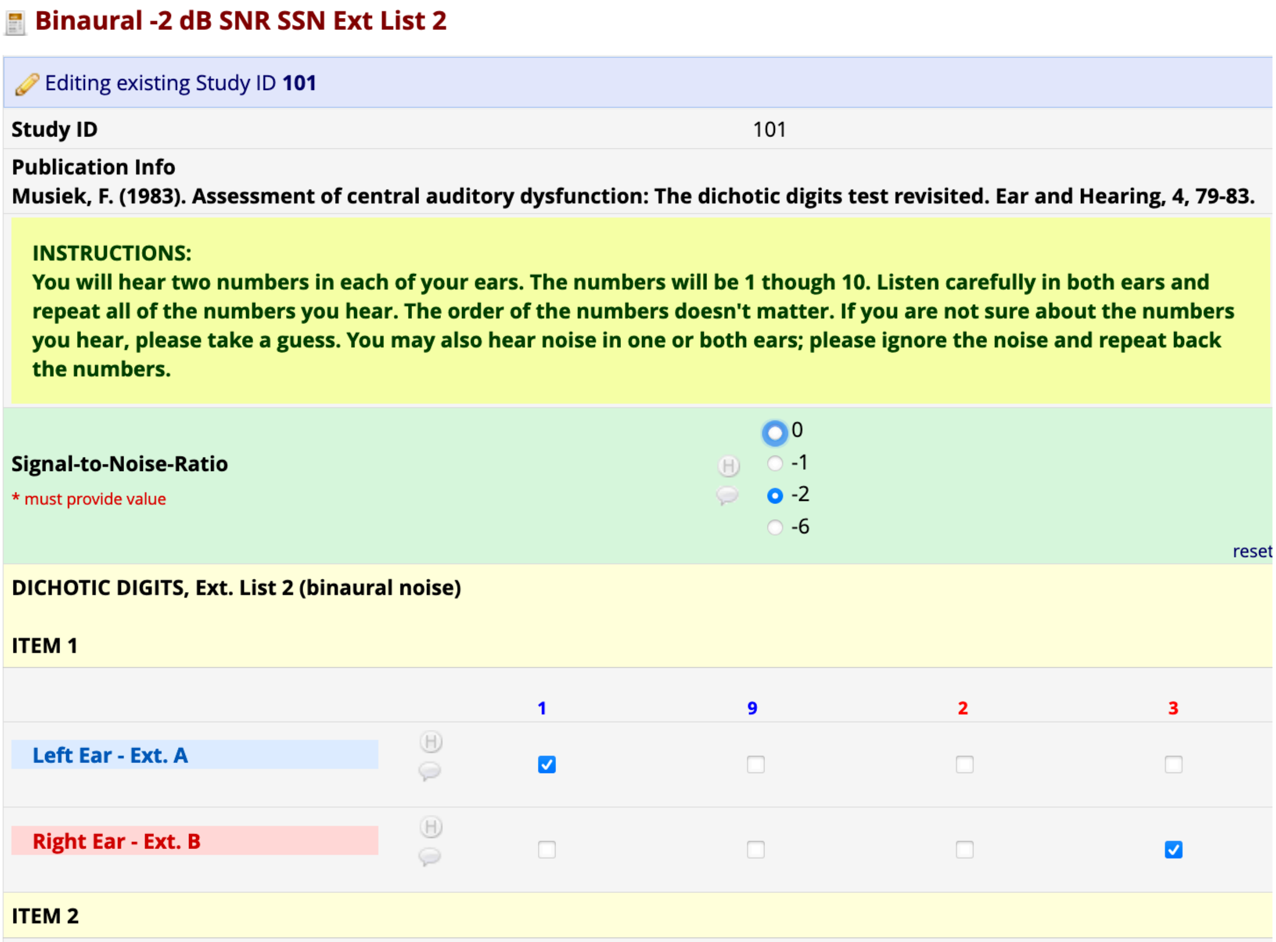
Participant Number
Pure Tone Screen
P F
SRT:
LE
RE

Test order (random)

Practice Items			
5	4	2	1
8	3	6	4
2	8	3	5

Test 1 (no noise)				Test 2 (binaural noise)			
10	3	9	2	1	9	2	3
6	10	1	2	5	9	1	6
9	2	3	4	4	2	1	8
9	3	4	1	5	6	8	9
3	8	5	9	5	10	2	8
1	8	3	6	3	2	1	4
5	8	6	9	5	2	3	6
5	10	4	8	2	1	10	3
9	4	5	6	4	10	5	3
5	6	3	1	6	8	4	9
2	9	1	6	2	5	3	4
3	5	1	4	3	9	2	10
2	1	4	6	2	8	1	3
9	1	3	10	5	4	8	6
5	9	1	6	1	5	2	6
2	8	6	5	4	3	1	5
4	10	8	6	6	1	10	4
3	10	4	8	10	1	5	4
1	5	6	2	6	4	3	5
9	6	3	4	9	5	6	3
LE Score		RE score		LE Score		RE score	

Appendix 4. Sample REDCap scoring screen, including standardized instructions.



Binaural -2 dB SNR SSN Ext List 2

Editing existing Study ID **101**

Study ID 101

Publication Info
Musiek, F. (1983). Assessment of central auditory dysfunction: The dichotic digits test revisited. Ear and Hearing, 4, 79-83.

INSTRUCTIONS:
You will hear two numbers in each of your ears. The numbers will be 1 though 10. Listen carefully in both ears and repeat all of the numbers you hear. The order of the numbers doesn't matter. If you are not sure about the numbers you hear, please take a guess. You may also hear noise in one or both ears; please ignore the noise and repeat back the numbers.

Signal-to-Noise-Ratio
* must provide value

0
-1
-2
-6

reset

DICHOTIC DIGITS, Ext. List 2 (binaural noise)

ITEM 1

	1	9	2	3
Left Ear - Ext. A	☑	☐	☐	☐
Right Ear - Ext. B	☐	☐	☐	☑

ITEM 2

Appendix 5. Test-Retest raw data.

	Study ID	504 Test	504 RT	605 Test	605 RT	701 Test	701 RT	803 Test	803 RT
Control	LE %	97.5	100	100	100	100	100	97.5	100
	RE %	100	100	100	100	100	97.5	97.5	97.5
	CombTotal	99	100	100	100	100	99	98	99
	DDS	-2.5	0	0	0	0	2.5	0	2.5
Bin -2	LE %	92.5	95	95	90	90	90	90	90
	RE %	97.5	95	100	95	87.5	92.5	100	90
	CombTotal	95	95	98	93	89	91	95	90
	DDS	-5	0	-5	-5	2.5	-2.5	-10	0
Mono R -2	LE %	100	100	100	90	100	100	100	100
	RE %	57.5	57.5	77.5	77.5	52.5	70	52.5	65
	CombTotal	79	79	89	84	76	85	76	83
	DDS	42.5	42.5	22.5	12.5	47.5	30	47.5	35
Mono L -2	LE %	55	70	92.5	90	72.5	80	80	80
	RE %	100	100	100	100	100	97.5	100	100
	CombTotal	78	85	96	95	86	89	90	90
	DDS	-45	-30	-7.5	-10	-27.5	-17.5	-20	-20
Bin -6	LE %	70	75	75	77.5	47.5	65	90	80
	RE %	65	90	82.5	75	57.5	70	90	82.5
	CombTotal	68	83	79	76	53	68	90	81
	DDS	5	-15	-7.5	2.5	-10	-5	0	-2.5
Mono R -6	LE %	100	100	100	100	100	100	100	100
	RE %	12.5	27.5	52.5	32.5	25	32.5	32.5	40
	CombTotal	56	64	76	66	63	66	66	70
	DDS	87.5	72.5	47.5	67.5	75	67.5	67.5	60
Mono L -6	LE %	22.5	42.5	52.5	57.5	30	65	22.5	37.5
	RE %	100	100	100	100	100	97.5	100	100
	CombTotal	61	71	76	79	65	81	61	69
	DDS	-77.5	-57.5	-47.5	-42.5	-70	-32.5	-77.5	-62.5

** Only two of these participants were included in the final data analysis.*

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