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Widespread auditory deficits in tune deafness

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Abstract

Objective—The goal of this study was to investigate auditory function in individuals with deficits in musical pitch perception. We hypothesized that such individuals have deficits in non-speech areas of auditory processing.

Design—We screened 865 randomly selected individuals to identify those who scored poorly on the Distorted Tunes Test (DTT), a measure of musical pitch recognition ability. Those who scored poorly were given a comprehensive audiologic examination, and those with hearing loss or other confounding audiologic factors were excluded from further testing. Thirty-five individuals with tune deafness constituted the experimental group. Thirty-four individuals with normal hearing and normal DTT scores, matched for age, gender, handedness, and education, and without overt or reported psychiatric disorders made up the normal control group. Individual and group performance for pure tone frequency discrimination at 1000 Hz was determined by measuring the difference limen for frequency (DLF). Auditory processing abilities were assessed using tests of pitch pattern recognition, duration pattern recognition and auditory gap detection. In addition, we evaluated both attention and short- and long-term memory as variables that might influence performance on our experimental measures. Differences between groups were evaluated statistically using Wilcoxon non-parametric tests and t-tests as appropriate.

Results—The DLF at 1000 Hz in the group with tune deafness was significantly larger than that of the normal control group. However, approximately one third of participants with tune deafness had DLFs within the range of performance observed in the control group. Many individuals with tune deafness also displayed a high degree of variability in their inter-trial frequency discrimination performance which could not be explained by deficits in memory or attention. Pitch and duration pattern discrimination, and auditory gap detection ability were significantly poorer in the group with tune deafness than the normal control group. Approximately one third of our participants with tune deafness displayed evidence of attention deficit with hyperactivity disorder (ADHD) on the Test of Variables of Attention (TOVA). TOVA scores were significantly correlated with gap detection scores, but not significantly correlated with any of the other experimental measures, including the DTT, DLF and auditory pattern discrimination tests. Short- and long-term memory was not significantly related to any of the experimental measures.

Conclusions—Individuals with tune deafness identified by the DTT have poor performance on many tests of auditory function. These include pure tone frequency discrimination, pitch and duration pattern discrimination, and temporal resolution. Overall, reduction in performance does not appear to derive from deficits in memory or attention. However, because of the prevalence of ADHD in those with tune deafness, this variable should be considered as a potentially confounding factor in future studies of tune deafness and its characteristics. Pure tone frequency discrimination varied

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widely in individuals with tune deafness, and the high degree of inter-trial variability suggests that frequency discrimination may be unstable in tune deaf individuals.

Introduction

Pitch is the attribute of auditory sensation by which sounds may be ordered on a scale from low to high. Pitch depends mainly on the frequency of the sound, but also on other features of the waveform and on sound processing by the listener (Hartmann, 1998).

Musical pitch perception is classified in two ways, relative pitch and absolute (or perfect) pitch. Relative pitch perception is the ability to properly discriminate the interval between successive pitches, such as the notes in a melody. Absolute pitch is ability to identify the pitch of an isolated note without the use of a reference tone, and may represent a unique form of auditory memory. Thus, individuals with relative pitch can easily identify a melody when starting at different notes (i.e. in a different key). However, unlike individuals with absolute pitch, they cannot easily determine *a priori* the key it is played in.

Pitch perception is also important in the identification and segregation of both speech and non-speech sounds (Shamma, 2004). Studies have demonstrated various neuroanatomical regions associated with pitch perception (Tramo et al., 2005, Johnsrude, Penhune, and Zatorre, 2000, Clark et al, 2002), but a number of aspects of pitch perception remain unclear (de Chevigne, 2004).

Deficits in musical pitch perception have been defined in several ways. The term tone deafness is widely used in this context, although this term does not best describe the deficits exhibited by affected individuals. Tune deafness is defined using the Distorted Tunes Test (DTT), in which the listener is required to determine whether each of 26 short familiar melodies is played correctly or not. The DTT primarily tests the ability of individuals to properly discriminate intervals between successive tones, which define a melody. The DTT has been widely used since the 1950's (Kalmus & Fry, 1980, Drayna et al, 2001), and is especially useful as a population screening tool. However, the DTT does not test many aspects of music perception or hearing. A more detailed and extensive test of music perception is the Montreal Battery of Evaluation of Amusia (MBEA), which tests fine-grained pitch discrimination and other detailed aspects of musical perception (Peretz, Champod and Hyde, 2003). Using the MBEA, a group of individuals have been defined as having congenital amusia, a disorder in which individuals fail to appreciate, perceive, or distinguish many aspects ofa musical melody in the absence of injury to the brain (Foxton, Dean, Gee, et al. 2004, Ayotte, Peretz, and Hyde, 2002; Hyde and Peretz, 2004). Congenital amusia has been associated with other music-specific impairments, such as the inability to remember or recognize a song (Ayotte, Peretz, and Hyde, 2002) or the inability to perceive temporal structure in music (i.e. lack of rhythm) (Della Balla, Peretz, and Aronoff, 2003).

In a landmark case study, Peretz et al.,(2002) reported pitch perception skills and other auditory abilities in one individual with congenital amusia. When asked to identify pitch changes inserted in a five-tone sequence and in a tone pair, this subject demonstrated a significant deficit in detecting changes in pitch. This deficit was more severe when the variant tone was lower in pitch than the reference tone.

Foxton, Dean, Gee, et al. (2004) investigated pitch-perception abilities in 10 adults with congenital amusia. Tests were administered to assess pitch perception, pitch pattern perception, and perceptual organization of sounds. The results showed a small overlap between the experimental group (amusics) and the normal control group, and the amusic subjects showed no impairment in their ability to perceptually organize sounds into distinct streams of high and low pure tones. However, the amusics demonstrated distinct deficits in more complex perception tasks that required the detection of segmented and gliding pitch changes. The amusics in this study displayed deficits in determining the direction of pitch change, and deficits in the detection of differences between pitch sequences. However, deficits in this group did not apparently extend to the time domain.

Deficits in musical pitch perception have been well documented in a small number of highly selected individuals (Foxton, Dean, Gee et al., 2004), and numerous studies have focused on the neural structures and functions that participate in pitch perception (de Cheveigne, 2004; Zatorre, Belin, and Penhune, 2002, Piccirilli, Sciarma, and Luzzi, 2000, Tramo et al. 2005). However the relationship between deficits in musical pitch perception and other auditory processing abilities, especially non-musical processing functions in the broader population of individuals with deficits in pitch recognition are not fully understood. In order to expand on the previous findings in the musical domain, we chose to focus primarily on audiological rather than musical measures in tune deaf individuals. The main goal of this research was to obtain a greater understanding of the auditory processing abilities in a population of randomly ascertained tune deaf individuals.

Central auditory processing (CAP, often simply called auditory processing, AP) refers to auditory functions that take place after sound energy has been received and nerve impulses initiated in the chochlea (Musiek, 2004). Auditory processing includes a number of functions crucial to the full analysis and comprehension of sound information. This includes dichotic functions such as sound localization, as well as high-resolution timing and pitch analysis of sounds, which are essential for the proper comprehension of speech (Gordon-Salant and Fitzgibbons, 2004). Studies of individuals initially identified because they have deficits in musical pitch perception may provide information about the mechanisms that operate in auditory processing, many aspects of which remain poorly understood.

Previous studies have relied heavily on subject self-selection and self-report in their enrollment of amusic individuals (Ayotte, Peretz, and Hyde, 2002; Foxton, Dean, Gee, et al., 2004; Peretz, Ayotte, Zatorre et al, 2002). However since this method can be susceptible to ascertainment bias (Sloboda, Wise, & Peretz, 2005), we enrolled individuals with tune deafness by screening a large, random population to identify individuals who performed poorly on the Distorted Tunes Test (DTT).

The DTT is a musical pitch recognition screening test that has been widely used in children and adults (Kalmus and Fry, 1980, Drayna, Manichaikul, de Lange, et al., 2001). The DTT consists of 26 short, unaccompanied melodic fragments in a synthesized piano timbre, plus spoken instructions, and has been recorded on a compact disc. In the DTT, individuals are asked to determine whether or not each tune is played correctly or incorrectly, and to report whether each melody is familiar or unfamiliar. Population performance on the DTT has been well characterized, and studies have shown scores in the U.S. population are largely independent of musical experience. The DTT has been used in a variety of perceptual and genetic studies and ideal for screening large populations for deficits in musical pitch perception (Drayna, Manichaikul, de Lange, et al., 2001). Such individuals have deficits similar to those defined as amusic using the MBEA, although they are formally defined as tune deaf rather than amusic in the context of this study.

The goal of the present study was to characterize other non-speech auditory processing functions, memory deficits, and ADHD in a randomly ascertained population of tune deaf individuals. To complement the existing information on musical auditory functions in amusia, we chose well characterized tests of AP outside the musical domain, including measures of pure tone frequency discrimination, temporal order processing, and gap detection. We also examined auditory and visual short term memory outside the musical domain.

METHODS

Phase I. Ascertainment and Recruitment

Eight hundred sixty-four (864) individuals, ages 15 – 60 years, were enrolled in the screening phase of this study by public written and oral appeal. All subjects provided written informed consent for this research, which was conducted under IRB-approved protocol 00-DC-0176 (NINDS/NIDCD/NIH). The DTT (available at http://www.nidcd.nih.gov/tunetest/dtt.asp and in hard copy from the corresponding author) was played on an Audiophase portable CD player (Model: CD-315), and delivered through Sony over-the-ear headphones (MDR-Q25LP). Ambient noise levels were reduced through the use of muff style hearing protectors (Husqvarna Model: 192766; Noise Reduction Rating 25 dB). The participants were asked to determine whether each melody was correct or incorrect and to report whether they were familiar with each of the 26 melodies. They also completed the Five-Minute Hearing Test, a written hearing questionnaire whose results have previously been shown to correlate with pure tone hearing thresholds (Koike, Hurst, and Wetmore, 1994). Participants were invited to continue in Phase II of this study if they met the following criteria: a) scored below the 10th percentile (≤18, the tune deaf group) or above the 60th percentile (≥24, the normal group) on the DTT, b) scored ≤15 on the 5-Minute Hearing Test (likely to have normal hearing) and c) had no self-reported cognitive, psychiatric, or neurological impairments.

Phase 1: Results

Five hundred twenty seven females and 337 males took the DTT. Figure 1 illustrates the distribution of scores on the DTT. These scores were similar to previously published results using this test (Kalmus and Fry, 1980;Drayna et al, 2001). The self-reported ethnicity of the participants was Asian (n= 48), Black (n=219), Hispanic (n=38), Native American (n=3), White (n=529), or Other (n=27).

Phase II: Enrollment and Procedures

Eighty three individuals scored in the lowest 10th percentile on the DTT and were invited to continue in the study. Seven of these individuals declined further participation. Seventy six individuals took the DTT a second time to confirm low performance, and were admitted to Phase II. A comprehensive audiologic evaluation was conducted on all Phase II participants, including measurements of pure tone and speech thresholds, word recognition ability, tympanometry, and otoscopy. A complete history was taken regarding tinnitus, aural fullness, otalgia, history of noise exposure and middle ear infections.

Eligibility requirements for inclusion in Phase II of the study were normal hearing sensitivity and no signs of active middle ear disease. Normal hearing was defined as air conduction thresholds ≤ 20 dB HL (American National Standards Institute, 1996) for octave frequencies from 250 through 8000 Hz. Normal tympanometry was defined as peak compensated static compliance between 0.3 and 1.5 mL and middle ear pressure between +50 to −100 daPa. Seven subjects were disqualified because they did not meet these criteria, and were referred to a physician for follow-up. Of the resulting 69 tune deaf subjects, 35 completed the full battery of subsequent auditory tests.

Sixty-nine individuals, 35 tune deaf and 34 normal controls, participated in the full study, and their characteristics are summarized in Table 1. All were native speakers of English and extensively experienced in U.S. culture, without overt or reported psychiatric disorders. The experimental group consisted of 35 individuals (21 females and 14 males) out of a total of 83 individuals classified as tune deaf in Phase I. None had received musical training or lessons on a musical instrument. The normal control group consisted of 34 age-, gender-, handedness-, and education-matched individuals (17 females and 17 males) who scored above the 60th percentile on the DTT (scores ≥24). The mean age of the tune deaf subjects was 25 years (range 17 to 54 years) and the mean age of the subjects in the control group was 27 years (range 17 to 50 years). Composite audiograms for the experimental and control groups are shown in Figure 2.

Phase II

Procedures and Stimuli—The following tests were conducted on all Phase II participants in a double walled sound-attenuating booth.

Difference Limen for Frequency (DLF)—The difference limen for frequency (DLF) was determined using an adaptive, four-alternative, forced-choice procedure (Hartmann, 1996; Turner & Nelson, 1982). This test tracks subject performance and adjusts stimuli to approach, over many trials, the minimum frequency difference a subject can perceive between adjacent pure tones. Such test paradigms are widely used in current psychoacoustic research (Fitzgibbons, 1998, Fitzgibbons, Gordon-Salant, and Barrett, 2007). Subjects were presented with a series of trials in which the task was to determine which of four tones was higher in pitch than the other three. Subjects responded by pressing one of four buttons on a control panel corresponding to the tone that was perceived to be higher in pitch. Feedback was provided after each answer by illumination of all 4 buttons in the case of a correct answer and no illumination of the buttons in the case of an incorrect answer. The variant tone occurred at a random position in each group of four.

The DLF was measured monaurally in the left ear for a 1000 Hz pure tone presented at 80 dB SPL. Signal duration was 250 msec (10 msec rise/fall) with a 500-msec interval between each tone. Signals were generated by a Tucker-Davis Technologies System 3, using an RP2.1 real time processor, controlled by SykofizX and PsychRP software, and routed through a headphone buffer (HB7) to Sennheiser HD265 earphones.

At the start of each trial, three 1000-Hz tones were presented along with one 1100 Hz tone, which was presented at a random position among the four tones. Upon a correct response, the frequency difference between the 1000 Hz reference tone and the variant tone was decreased in half-log steps, (each step differing by $10^{1/2}$, or 3.16-fold in frequency), which continued until the subject answered incorrectly. Upon an incorrect answer, the difference between the reference tones and the variant tone was increased (a reversal) until the subject again produced two correct answers, at which point the difference was again decreased (another reversal) until the subject answer incorrectly. This adaptive procedure continued until there were 14 reversals in the stimulus direction, which together resulted in seven successive approaches to the minimum frequency difference the subject could detect. This constituted one trial run, and trial runs were repeated until stopping criteria, outlined below, were achieved Estimates of each subject's DLF from one trial run were obtained using the adaptive rule that estimates 70.7% correct discrimination on the psychometric function (Levitt, 1971). The DLF threshold estimate for each trial run was calculated as the mean of the midpoints between the frequency of the higher and lower tones that represented the final nine reversals during the trial run.

DLF threshold estimates were obtained from a minimum of eight trial runs, and testing continued until criteria were met for stability with no further improvement. Stable performance was defined as three consecutive trial runs that varied by no more than 30% in DLF threshold. No further improvement was determined by calculating a running average of the most recent three trial runs at the conclusion of each trial run. This was continued until the last running average was larger than the previous one. Testing ceased when both criteria were met simultaneously. Each participant's overall DLF threshold was calculated as the mean of the thresholds of the last six trial runs.

Auditory Processing Tests—All other test stimuli, instructions, and practice items were recorded on a custom CD using Adobe Audition (v. 1.5, Adobe Software Systems, 2001). The CD was played on a Denon Model DCD-690 routed through a GSI-61 clinical audiometer, and presented via ER3A insert earphones. Participants responded in written format, using closed-set answer sheets designed for each of the tests. Each recorded test included examples and practice items. A carrier phrase announcing each item was included to assist subjects' ability to maintain the correct place on the answer sheet.

Pitch Pattern Test (PPT)—We used a CD version of a commercially available PPT (Auditec, St. Louis), modified to include a carrier phrase prior to each pattern presentation. The PPT was presented monaurally at 50 dB SL (re: 1000 Hz) to each ear successively. Test items are composed of three 200-msec tone bursts (10-msec rise-fall times), separated by 150-msec inter-stimulus intervals. Each item consists of combinations of two frequencies, 1430 Hz and 880 Hz, which are designated as high frequency (H) and low frequency (L), respectively. There are 60 trials in the test,, consisting of six patterns, each presented 10 times in random order.. Participants were instructed to circle the letter pattern corresponding to the pitch sequence they heard (HHL, HLH, HLL, LHH, LHL, LLH). Subjects were instructed to guess in cases they were unsure of the pattern. The first ten patterns were given as practice and scores were recorded as number of correct pattern identifications out of the total of 50 for each ear.

Duration Pattern Test (DPT)—We used a CD version of a commercially available DPT (Auditec, St. Louis), modified to include a carrier phrase prior to each pattern presentation. The DPT was presented monaurally at 50 dB SL (re: 1000 Hz) to each ear successively. Test items are composed of three 1000-Hz tone bursts (10-msec rise-fall times), separated by 300-msec inter-stimulus intervals. Each item consists of combinations of two stimulus durations, 250 and 500 msec, designated short (S) and long (L), respectively. There were 30 duration patterns, six patterns with five randomizations. Participants were instructed to circle the letter pattern corresponding to the duration sequence they heard (SSL, SLS, SLL, LSS, LSL, LLS). Subjects were instructed to guess in cases they were unsure of the pattern. Scores were recorded as the number of correct pattern identifications out of the total of 30 in each ear.

Gap Detection - Gap in Noise Test (GIN)—The GIN (Musiek, Shinn, Jirsa et al, 2005) was administered monaurally to the right ear at 50 dB SL (re: 1000 Hz). The GIN consists of 35 six-second intervals of broadband noise that contain zero to three short intervals of silence or gaps. Gap durations are 2, 3, 4, 5, 6, 8, 10, 12, 15, or 20 msec. Each gap duration is presented six times during the test for a total of 60 gaps. Gap size and temporal location in the noise segments are pseudorandomized (Musiek, Shinn, Jirsa, et al, 2005). The listeners indicated how many gaps were perceived within each noise interval by circling the corresponding number on an answer sheet, containing the options 0, 1, 2 and 3. If the number of reported gaps was less than the number present in the noise segment, it was assumed that the shortest gap(s) was not perceived. If the number of reported gaps exceeded the number of gaps present in the noise segment, this was scored as a false positive. In the manner of Musiek et al. (2005), two measures of gap detection ability were calculated; percentage correct and estimated gap threshold. The estimated gap threshold was calculated as the shortest gap interval correctly identified in four of its six presentations, with maintenance or improvement of performance for longer gap durations.

Memory Tests—We sought to test aspects of memory that have not been well characterized in these subjects previously. Auditory short-term memory was evaluated by the Memory for

Digits Test and the Nonword Repetition Test. Both are subtests of the Comprehensive Test of Phonological Processing (CTOPP) (Torgensen and Rashotte, 1999), a widely used clinical measure. Memory for Digits is a 21-item sub-test measuring the extent to which a subject can repeat a series of numbers ranging in increasing length from two to eight digits. Nonword Repetition is an 18-item test measuring a subject's ability to repeat nonsense words that range in length from three to 15 phonemes. Nonword Repetition is a measure of phonological memory. Both tests were recorded on a custom CD. The items were presented diotically using ER3-A insert earphones. The examiner recorded the participant's answers on a corresponding response sheet. Scores for the Memory for Digits test and Non-Word Repetition tests were calculated as the number of correct answers out of a total of 21 and 18, respectively.

To measure additional aspects of memory that require recall from long term memory, we used the Rapid Naming Test, a subtest of the CTOPP (Torgenson and Rashotte, 1999), which assesses a subject's ability to label a series of items that they see as quickly as possible. This test consists of four sections; one contains digits, one contains letters, one contains colors, and one contains objects. Each section presents 72 test stimuli arrayed in random order in four rows and nine columns on each of two pages. Subjects are instructed to name items from left to right until all items in that section have been named. The time to complete each section was timed by the examiner. The individual's score was the total time, in seconds, required to name the objects in each series.

Attention Testing—The Test of Variables of Attention (TOVA) was used to measure attention and to determine ADD/ADHD scores in 29 of the 35 tune deaf subjects who were available to take this test (Greenberg, Ross, Crosby, 1992; Leark, Dupuy, Greenberg et al. 1996, Clifford and Kindschi, 1996). The TOVA was administered on a Dell Latitude PC laptop computer running MS DOS, played through external Multi-media Speaker System YT-630. Both the visual and auditory attention tests were administered to all subjects, but because the auditory attention test requires discrimination between tones of two different pitches, this measure was not used to assign ADD/ADHD scores.

Statistical Analysis—Results were analyzed with the Statistical Package for the Social Sciences (SPSS) version 15.0 (Nie, Hull, and Bent, 2006). Data distribution was tested for normality and transformed when necessary. On non-normally distributed data, the non-parametric Wilcoxon Test was used. The two-tailed t-test was performed on normally distributed data, and also on cubic transformations of non-normally distributed data for additional comparison. Correlation was determined by calculation of Pearson's r.

RESULTS

Difference Limen for Frequency

Performance of one tune deaf and one normal control subject are shown as examples in Figures 3a and 3b. Each point on the graph represents the DLF threshold estimate for each trial run. In figure 3a, the normal control subject completed 12 trial runs, and this subject's overall DLF was 7 Hz, with a variance across all trial runs of 4 Hz. Figure 3b presents the performance of one tune deaf participant over 16 trial runs. This participant's overall DLF was 136 Hz, and the variance was 80 Hz. In contrast to the control participant's performance, the tune deaf subject not only had a higher overall DLF, but also displayed a larger variance in performance across trial runs.

The mean DLF of the normal control group over all trial runs was 7 Hz (SD= 3 Hz). The tune deaf participants as a group scored significantly poorer than normal controls on the DLF, and outside the normal range, which was defined as DLF scores within 1 Standard Deviation of the mean. The mean DLF of the tune deaf group was 35 Hz (SD=34 Hz) (Figure 4). This difference was highly significant ($p<0.0001$, Wilcoxon Test). Difference limen for frequency thresholds varied widely among individuals with tune deafness, ranging from 6 Hz to 136 Hz. In addition, 11 (31%) of 35 tune deaf individuals had DLFs within one standard deviation of the mean of our normal control group. The tune deaf participants as a group also displayed higher variance across trial runs. While the normal controls had a mean standard deviation of 2.4 Hz over their DLF trial runs, the mean standard deviation of the tune deaf participants across their trial runs was 14.0 Hz.

In light of the frequent occurrence of ADD/ADHD in our participants with tune deafness, we performed further analyses to examine the hypothesis that the 31% of tune deaf subjects who scored within the normal range on the DLF performed poorly on the DTT because of ADD/ ADHD, not because of deficits in auditory pitch or frequency discrimination.

Of the 29 participants with tune deafness screened for ADD/ADHD, 11 (37%) displayed TOVA scores less than −1.80, indicative of deficits in attention (Clifford and Kindschi, 1996). Of the 11 tune deaf participants who had normal DLF's, 9 scored above −1.80 on the TOVA. In addition, the pairwise correlation between tune deaf participants' DLF scores and their TOVA scores was very low ($r=0.07$) demonstrating that these two measures are largely unrelated in the tune deaf subjects. This suggests that attention deficits were not the cause of low DTT scores in tune deaf individuals with normal frequency discrimination i.e. DLF scores within one standard deviation of the normal mean.

Pattern Discrimination

Performance on the PPT and DPT are shown in Figure 5 and Figure 6. The results of the Wilcoxon test showed no significant difference between left ear and right ear within each group on both measures. The difference between the left and right ears of the normal controls on both measures was not significant $p = 0.7049$ PPT, and $p = 0.5539$ DPT. The difference between the left and right ears for the tune deaf group on both measures was not significant ($p = 0.9578$ PPT, and $p = 0.7325$ DPT).

Participants with tune deafness had lower scores than normal controls on the PPT (Figure 5). When averaged across both ears, the mean score of the control group was 57.1, while the mean of the tune-deaf group was 44.8 ($p = 0.0001$, Wilcoxon Test).

The mean DPT score of the control group was 28.7, while the mean score of the tune-deaf group was 23.6 ($p = 0.0001$, Wilcoxon Test). This difference remained statistically significant when the participants with tune deafness and ADD/ADHD were removed (p=.0041), indicating that temporal order processing is affected in tune deafness.

Gap Detection

Performance on the GIN is shown in Figures 7a and 7b. Individuals with tune deafness exhibited significantly poorer gap detection abilities than normal controls, despite both groups scoring in the normal range (thresholds of ≤ 6 ms or ≥ 50% correct (Musiek et al., 2005). The mean score for the control group was 46.4% (SD = 4.1), and the mean score for the tune deaf group was 43.3% (SD = 5.7) (Figure 7a). The mean gap detection threshold for the control group was 4.2 ms (SD = 0.8), and the mean for the tune deaf group was 4.7 ms (SD=1) (Figure 7b). These differences were significant ($p = .0155$ for the number of gaps detected and $p= .0170$ for gap in msec, t-test). However, when the participants exhibiting both tune deafness and ADD/ADHD were removed, these differences were no longer statistically significant (p=0.0741, t-test), although this trend suggests that gap detection may be affected in tune deafness.

Tests of Auditory Short-term Memory

The performance of tune deaf and normal subjects on memory tests is shown in Figures 8a and 8b. Figure 8a shows the results of memory for digits and Figure 8b shows the results for non-word repetition. On the memory for digits task, scores were normally distributed and the t-test was applied. The scores of participants with tune deafness were not significantly different from controls (p=0.29, t-test) on this test. The scores on the non-word repetition task were not normally distributed, and the non-parametric Wilcoxon Test was applied. Although the difference between the participants with tune deafness and the normal controls failed to reach formal significance (p = 0.0541), it is suggestive of a deficit in this task, which requires phonological (word sound) memory, in the tune deaf group.

Tests of Long-term Memory

Figure 9 a – d shows the results of the four rapid naming tests. Performance on these tests was within normal range for all subjects, and not significantly different between participants with tune deafness and normal controls (Rapid Letter Naming p=0.2864, Wilcoxon Test; Rapid Digit Naming p = 0.3887, Wilcoxon Test; Rapid Object Naming p=0.9448, t-test; Rapid Color Naming p=0.2406, t-test).

Correlation of performance across tests

To help quantify the generality of the auditory deficits our tune deaf subjects, we performed an analysis to compare scores on different auditory measures in our subjects, with the results shown in Table 2. Tests performed monaurally in each ear separately (Pitch Pattern Test and Duration Pattern Test) showed very high correlations (>.85) between scores obtain in different ears, and no significant difference in performance between ears.

There was little correlation between scores on the auditory processing tests (PPT, DPT, and GIN) and performance on either the DTT or the DLF. The strongest correlation observed was between DLF and GIN (in ms., Spearman Correlation Coefficient = −.195), although this was not significant (prob > |r| under H) = 0.265). Substantial correlations, ranging from .35–.75, were observed between scores on the pitch pattern, duration pattern, and gap detection tests, Correlations between scores on the memory tests and those on all the non-memory tests were generally low, with the exception of moderate correlations (.20–.40) with the Duration Pattern and gap detection tests, suggesting a role for memory in performance on these auditory processing tests.

DISCUSSION

We used the DTT to identify a population of individuals with tune deafness. Several factors could have been responsible for low DTT scores in this group. One likely source of a low DTT scores is hearing impairment, and indeed, seven subjects (8%) were disqualified in the Phase I screening portion of the study because of hearing deficits. Another source of poor performance could have been deficits in attention. Our results suggest that ADD/ADHD was common among the tune deaf participants and was also present in the control group. However, the low correlation of scores on the TOVA with those on the DTT suggests that attention deficits are not the primary source of low DTT scores. A third possible source of low DTT scores could have been memory deficits. Such deficits may have caused difficulties in judging whether or not melodies are played correctly. Because we wished to examine memory as broadly as possible, we used well-characterized tests outside the musical domain, as musical memory tests have been employed previously in congenital amusia (Ayotte, Peretz, and Hyde, 2002). As evaluated by rapid naming tests, long-term memory was found to be normal in our tune deaf group. Short term auditory memory was also normal in our subjects. Our results, combined with previous results obtained in a smaller number of individuals with congenital amusia

(Ayotte, Peretz, and Hyde, 2002), indicate a broad array of memory functions remain intact in tune deafness. Our data support and extend previous findings that have concluded that abnormalities in pitch perception underlie deficits in the perception of music (Ayotte, Peretz, and Hyde, 2002; Hyde and Peretz, 2004; Koelsch and Siebel, 2005). In addition, we found that deficits exist in a range of auditory pitch discrimination and frequency discrimination abilities in tune deaf individuals. Our tune deaf group had significantly larger DLFs than the normal control group. This measure is distinct from a number of other pitch recognition tests employed previously. Previous tests have measured gliding pitch detection, pitch sequence difference detection and a number of other dynamic stimuli (Foxton et al, 2004). The DLF, which uses one variant pure tone and a reference pure tone, measures a fundamental aspect of auditory processing that may involve other, subcortical areas of auditory processing. In addition, our tune deafness group performed significantly poorer on pitch pattern recognition, gap detection, and duration pattern recognition tasks.

Individuals in our study were identified as tune deaf because they reproducibly scored 18 or below on the DTT. However, there was wide variation in DLF and PPT scores in these tune deaf individuals. In particular, a number of participants with tune deafness performed within the normal range on both of the DLF and PPT. This suggests that the tune deaf population is heterogeneous in its ability to process both frequency and pitch. It may be that there are two types of tune deaf individuals: those who have deficits in pure tone frequency discrimination and those who have normal frequency discrimination. Further analysis of the tune deaf individuals who have normal pure tone frequency discrimination could lead to the identification of new aspects of sound perception and sound processing in humans.

The heterogeneity in DLF scores among our participants with tune deafness raises the question of whether frequency discrimination was a major determinant of performance on the other auditory processing tests we administered. If so, we would expect DLF scores would be correlated with auditory processing test scores. However, this was not the case, and the participants with tune deafness with normal DLF scores did not perform significantly different than those with abnormal DLF scores on any of the auditory processing tests.

Our frequency discrimination test differed somewhat from tests used in previous studies of pitch recognition, which have used other procedures and stimuli (Peretz, Ayotte, Zatorre, Mehler, Ahad, Penhune, et al., 2002). To focus on frequency perception rather than musical pitch perception, our DLF test employed non-musical frequencies, using half-log frequency differences rather than semitone musical pitch differences. The frequencies of the tones used in the DLF did not correspond to any standard notes on the western musical scale. At the 1000 Hz frequency of our reference tone, the mean DLF of our tune deaf subjects was 35 Hz, which corresponds to approximately one half semitone (35 Hz vs. 59 Hz for the difference between the notes “B” and “C”) in this frequency range. This is in close agreement with the degree of musical pitch perception impairment reported in previous studies of amusic individuals (Hyde and Peretz, 2004). Our adaptive paradigm and stopping criteria incorporated subject training within the test to account for learning effects. Trials and trial runs were repeated until subjects displayed no further improvement and stable performance.

Our DLF test employed pure tones rather than the complex (piano) tones employed in other studies (Peretz et al., 2002). This helped to insure that our study was specifically measuring frequency perception, and not pitch perception influenced by overtones, timbre, or other acoustical information present in complex tones.

We expected our subjects could show learning effects during the course of the DLF test, and that their DLF thresholds would decrease over repeated trial runs (Foxton et al., 2004). We did not observe this, which suggests that in agreement with previous studies, learning did not significantly affect frequency discrimination using our test paradigm (Foxton et al., 2004). Thus, our DLF test appears to measure an innate ability in adults, consistent with that suggested by other researchers (Peretz, Ayotte, Zatorre, et al., 2002)

The other notable aspect of our DLF test results was the inter-trial variation in performance by tune deaf participants. The minimum detectable frequency difference varied widely across successive trial runs in this group. This outcome was unlikely to have come from stochastic variation for two reasons. First, this variation did not occur in normal controls. Normal subjects displayed very stable frequency discrimination across successive trial runs (a mean of 8.7 Hz), with a low standard deviation. Second, each trial consisted of a minimum of 42 test stimuli, with a minimum of 14 reversals of stimulus presentation. This constituted at least seven successive approaches to the respondent’s minimum detectable difference during each trial run. The extent of variation during the successive trial runs suggests that frequency perception may be unstable in tune deaf individuals within the time frame of this test. While a fraction of the tune deaf individuals performed in the normal range on the DLF test, the converse was not true, in that none of the normal control individuals scored in the abnormal range. This suggests the DLF test is more robust for confirming normal pitch perception status than it is for demonstrating musical pitch perception deficits.

Temporal processing is of particular interest in tune deafness. Temporal measures such as rhythmicity have been previously examined in a limited group of amusic subjects (Hyde and Peretz, 2004) and found to be largely normal. The DPT and the PPT both reveal deficits in temporal order processing in our tune deaf subjects. Poor pitch pattern recognition was expected in the tune deaf group, but poor duration pattern recognition was not. However our results may not represent a contradiction with the results of Hyde and Peretz, as temporal order processing measured by the DPT and the PPT is quite different than the comprehension of rhythm in music, which is a substantially different stimulus compared to those in the DPT and the PPT. Because musical rhythm is characterized by a continuous and repetitive auditory stimulus, it could well employ functions different from those used in the discrete and separated stimuli in the temporal order tests we used.

The GIN also measures a form of auditory temporal resolution. It is important to note that all participants in both the tune deaf group and the normal control group performed within the normal range. However the scores were significantly poorer in the tune group compared to the control group based on both the percentage of correct answers and on gap detection thresholds. While it is unlikely that such small differences are significant in a clinical audiology setting, they reinforce the view that temporal processing is affected in tune deafness.

Auditory temporal processing thus appears to be affected in several different ways in tune deafness. The DPT measures ordering of auditory stimuli over the course of trials about one second in length. The GIN measures the detection of millisecond-length gaps in noise, and thus the DPT and the GIN test perception on very different time scales. Thus the functional extent of the deficits and the sparing of auditory temporal processing in tune deaf/amusic individuals is now a question of some interest..

Previous studies have provided evidence for differences between brain hemispheres in the processing of musical sounds versus non-musical sounds (Peretz, 2001, 2002, Koelsch et al 2002), so it was of interest to determine whether asymmetries in auditory processing would be significant in individuals with tune deafness. In the two auditory processing tests in which each ear was tested separately (the PPT and the DPT), the performances were not different between ears, and thus we saw no evidence for lateral asymmetry in tune deaf subjects.

Because scores on tests of memory were normal in the tune deaf group, we expected that scores on memory tests would show only weak correlations with their scores on any of the auditory tests. This was generally the case, however scores on the Rapid Dignit Naming and Rapid Object Naming tests often showed moderate negative correlation with the pitch and auditory processing tests in tune deaf individuals (Table 2). Taken together, our results raise the possibility that not only is memory unimpaired in tune deaf individuals, it may be modestly enhanced.

Correlations between other tests provide some additional intriguing findings. Scores on gap detection, pitch pattern detection, and duration pattern detection showed low correlation with each other in tune deaf subjects. This suggests that although these functions are impaired in tune deaf individuals, these deficits are not obligatorily related. In addition, scores on the DTT did not show high correlation with DLF scores in tune deaf individuals. This is consistent with our observation that many tune deaf individuals score normally on the DLF. It also suggests that tune deafness, which is the inability to perceive the correct relation between successive pitches, is not the same as a deficit in pure tone frequency discrimination. Finally, scores on both the DTT and the DLF showed substantial correlation with scores on the duration pattern, pitch pattern, and gap detection tests. This reinforces the view that perception of auditory temporal information is often co-impaired with pitch and frequency perception.

Deficits in performance on a number of different auditory tests have been observed previously in amusic subjects, at it has been suggested that such deficits may form a cascade originating with a congenital pitch processing defect (Peretz et al, 2002; Foxton, Dean, Gee, et al, 2004). At the current time, it is not clear which of the many auditory deficits we have identified are primary in this disorder and which are secondary. They could be related to each other in a cascade fashion, or they could be associated in other ways.

Conclusion

We hypothesized that tune deafness is a disorder that extends to other auditory functions beyond musical pitch recognition. On all measures of auditory processing that we examined, the tune deaf group scored significantly poorer than the normal controls. Our results support the view that both frequency (tonotopic) information and timing (temporal) information play an important role in the processing of both music and non-musical sounds. It is clear, however, that tune deaf individuals vary widely in their auditory processing functions. Our results suggest that future stratification of the tune deaf population may provide additional insights into these aspects of auditory processing.

Acknowledgements

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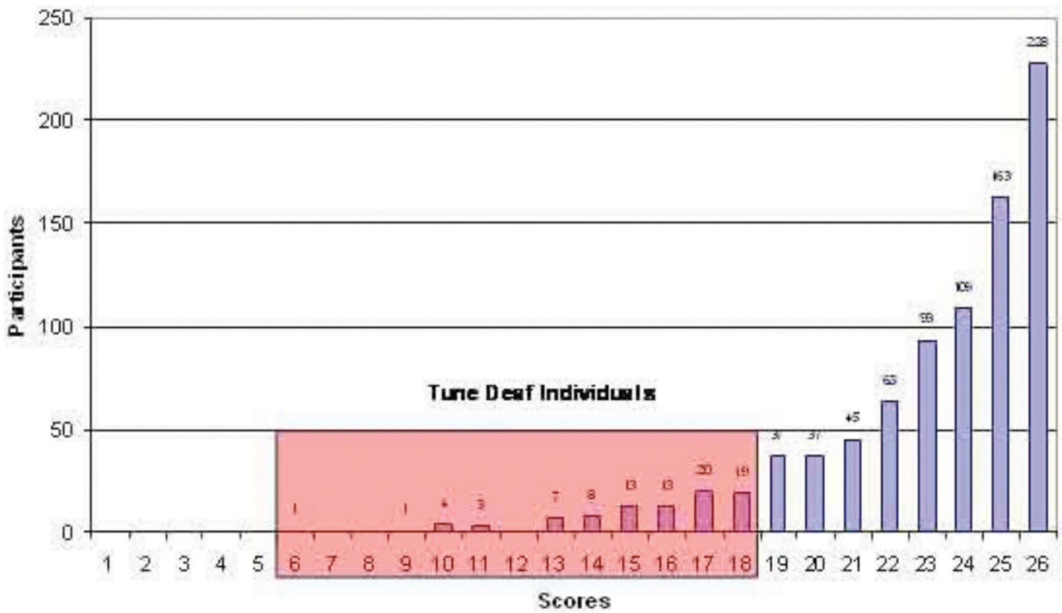


Figure 1.
Distribution of Scores on the Distorted Tunes Test (N=864).

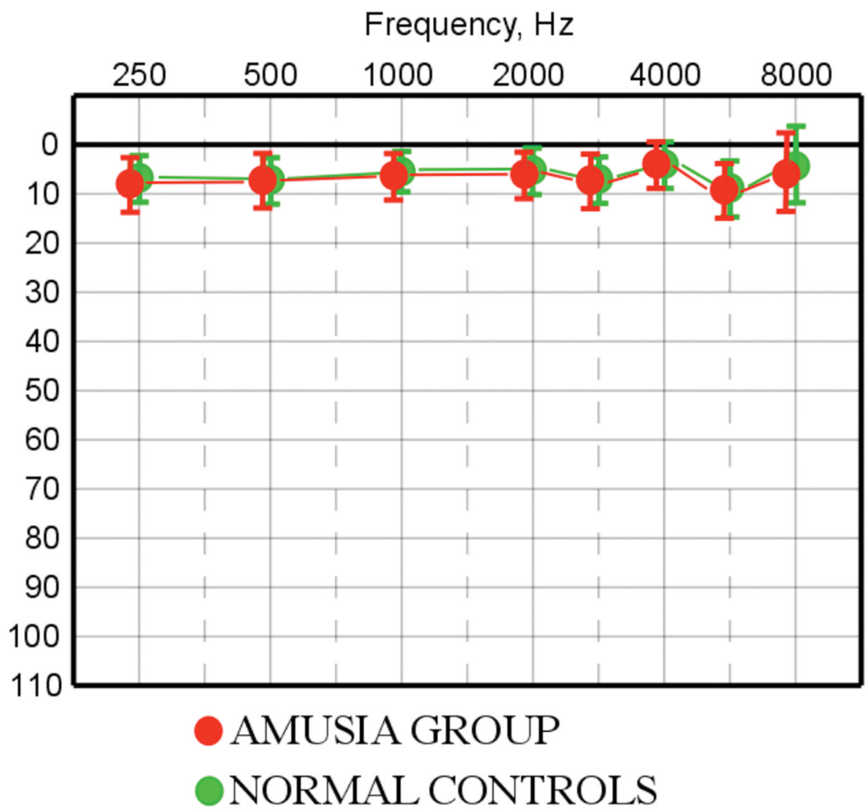


Figure 2.
Composite audiograms for the experimental (N=35) and control (N=34) groups.

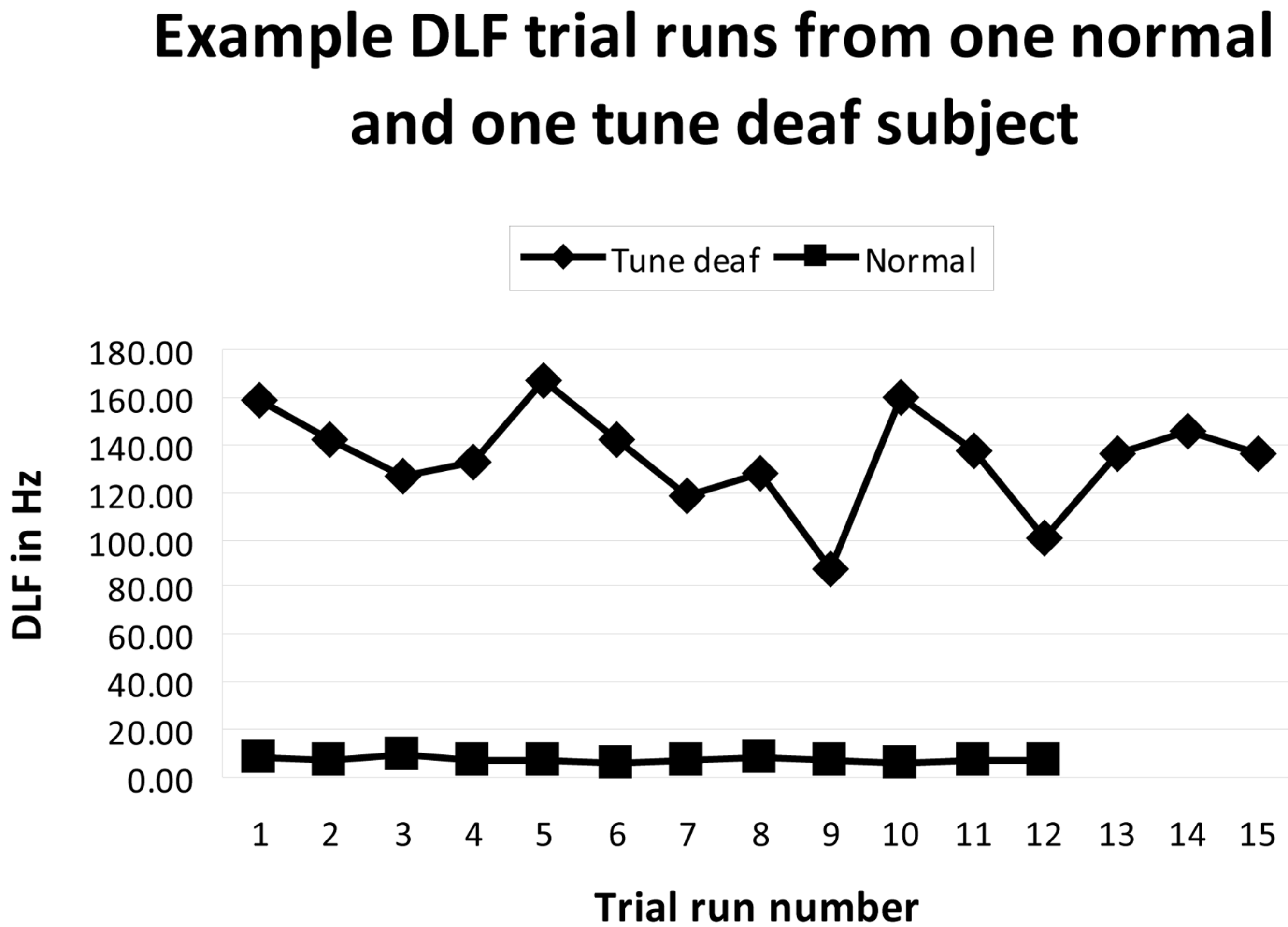


Figure 3.
Example DLF trial runs from one normal and one tune deaf subject

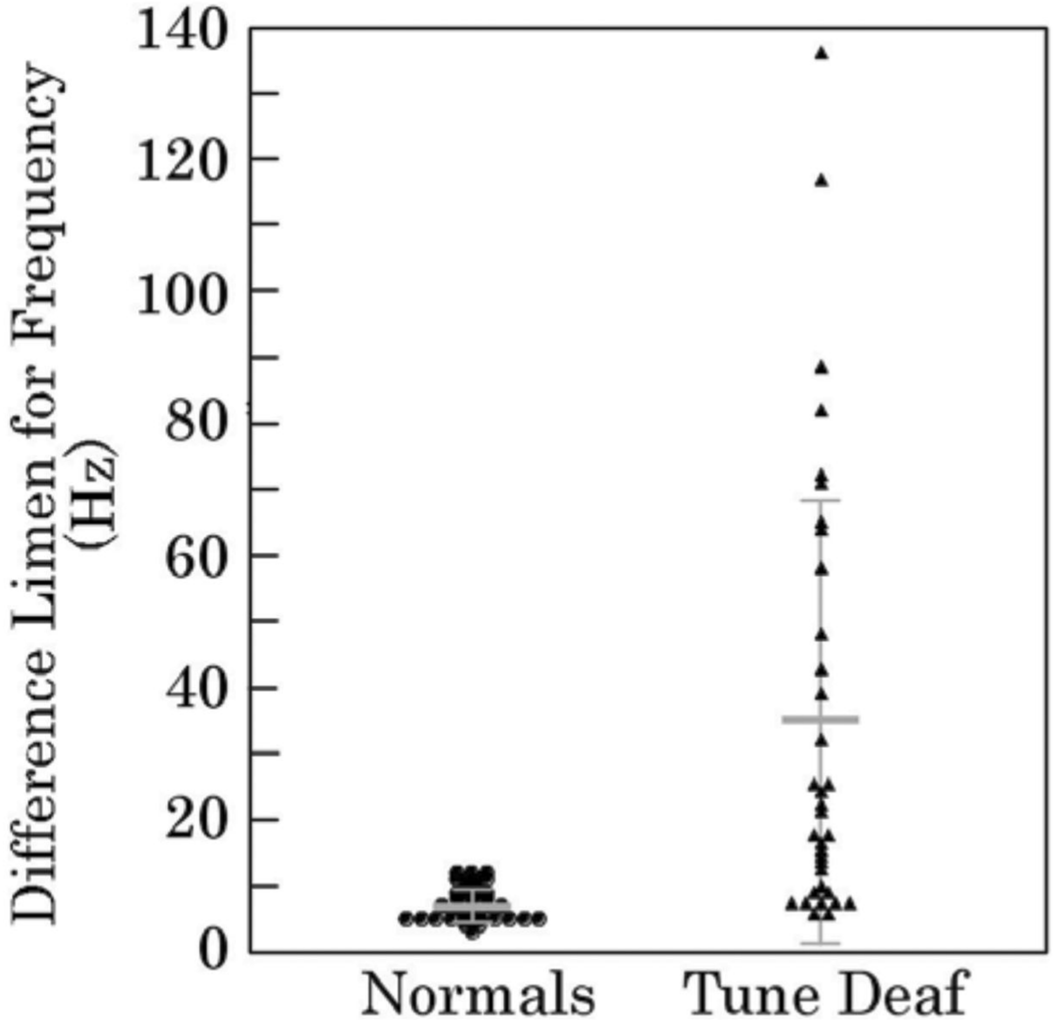


Figure 4.
Performance of Normal and Tune Deaf Subjects on Difference Limen for Frequency Test

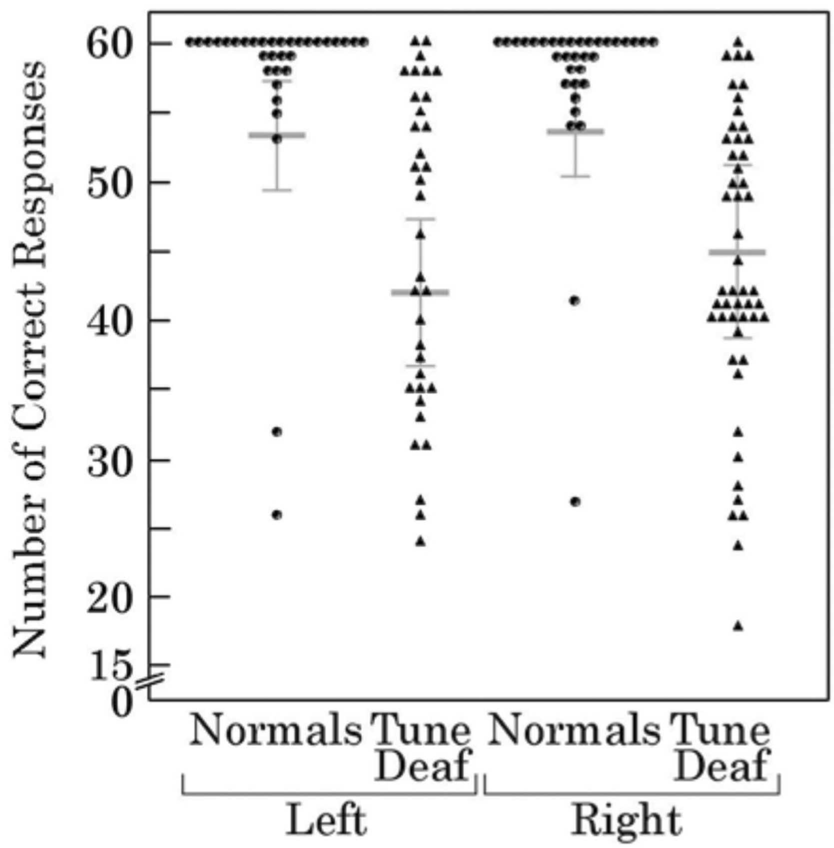


Figure 5.
Performance of Normal and Tune Deaf Groups on Pitch Pattern Test.

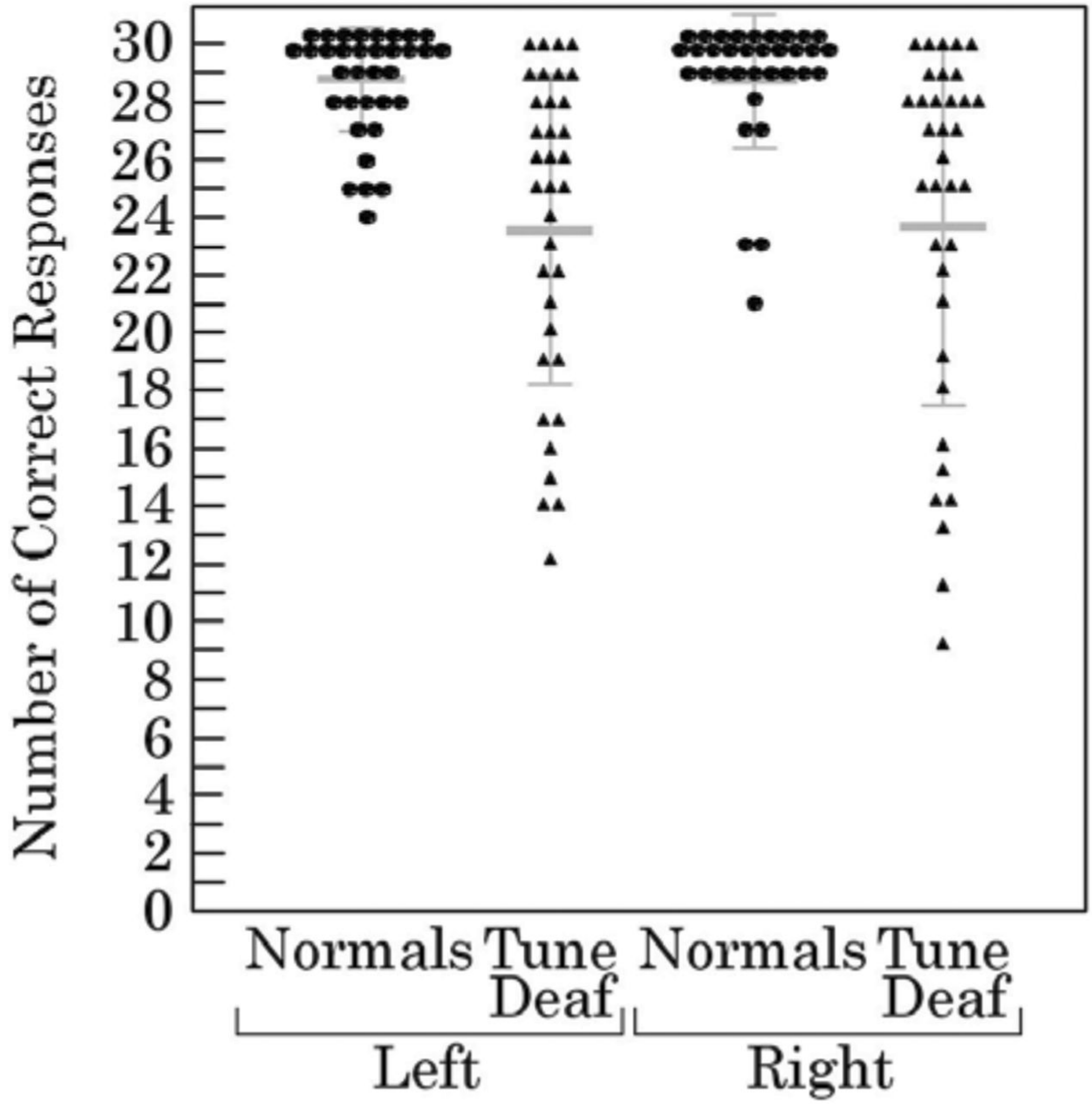
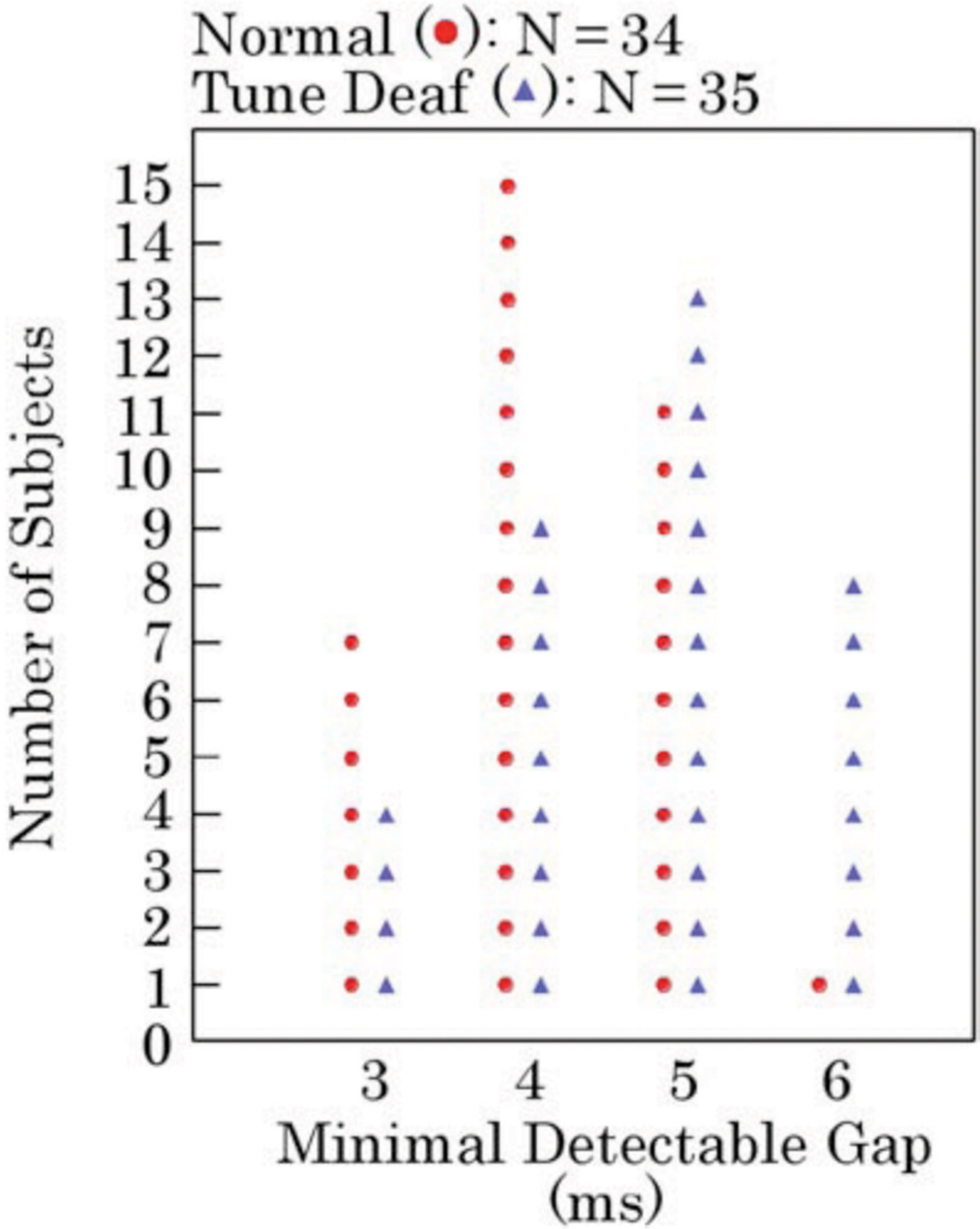


Figure 6.
Performance of Normal and Tune Deaf Groups on Duration Pattern Test.


Normal (●): N = 34
Tune Deaf (▲): N = 35
Number of Subjects
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
3
4
5
6
Minimal Detectable Gap (ms)

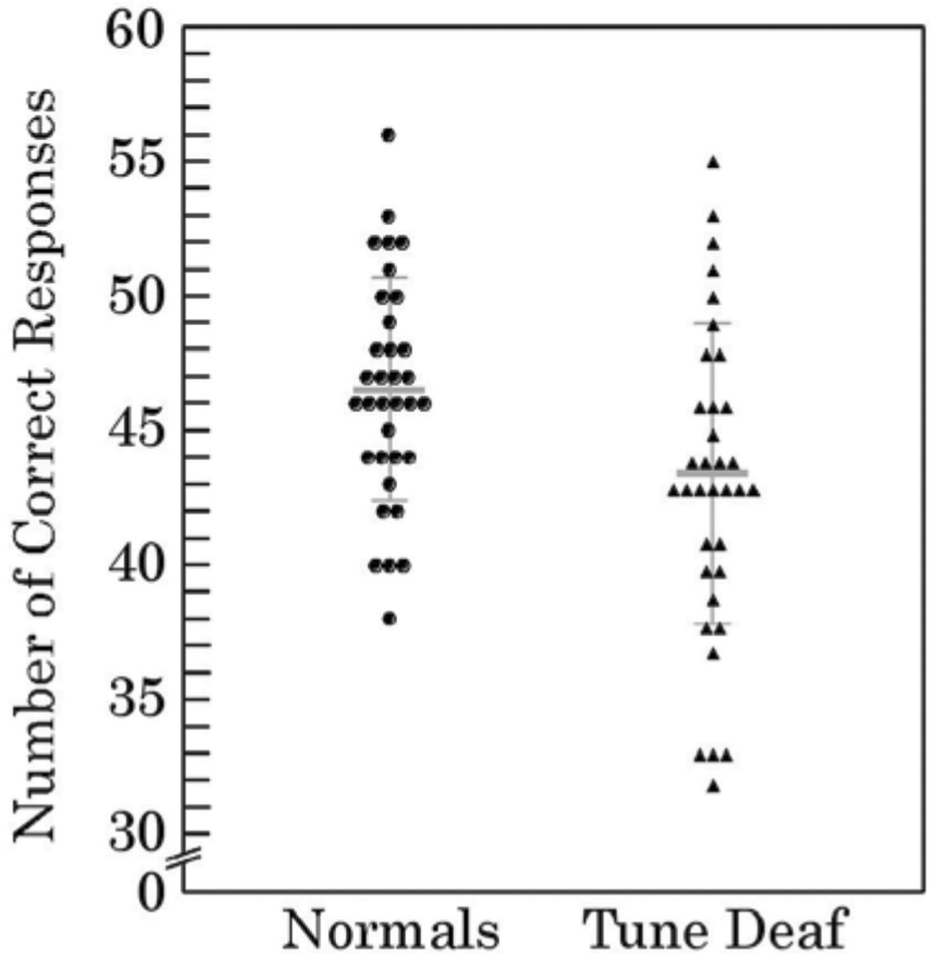


Figure 7.
Figure 7a. Performance of Normal and Tune Deaf Groups on Gap In Noise Test.
Figure 7b. Performance of Normal and Tune Deaf Groups on Gap In Noise Test.

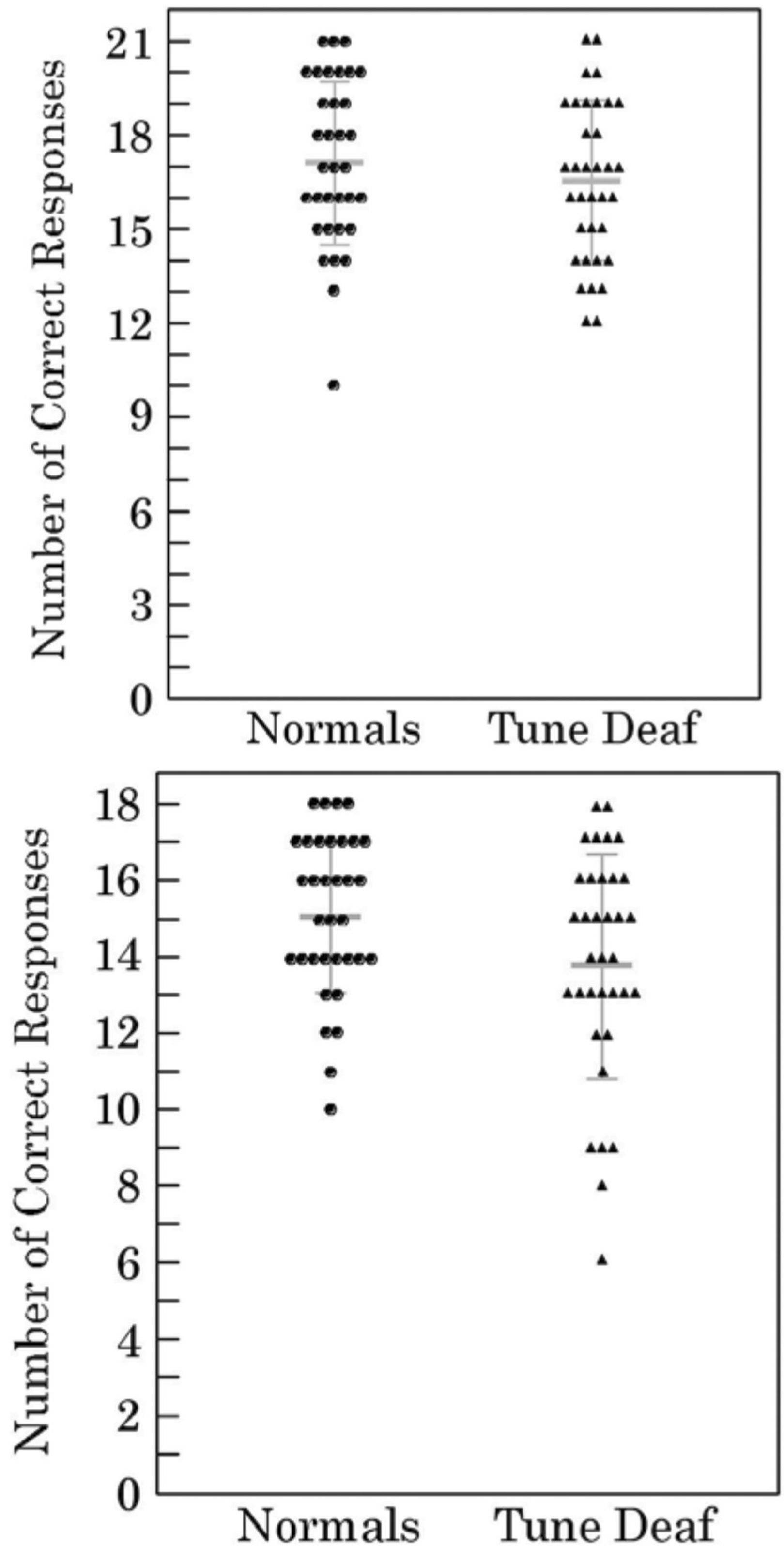
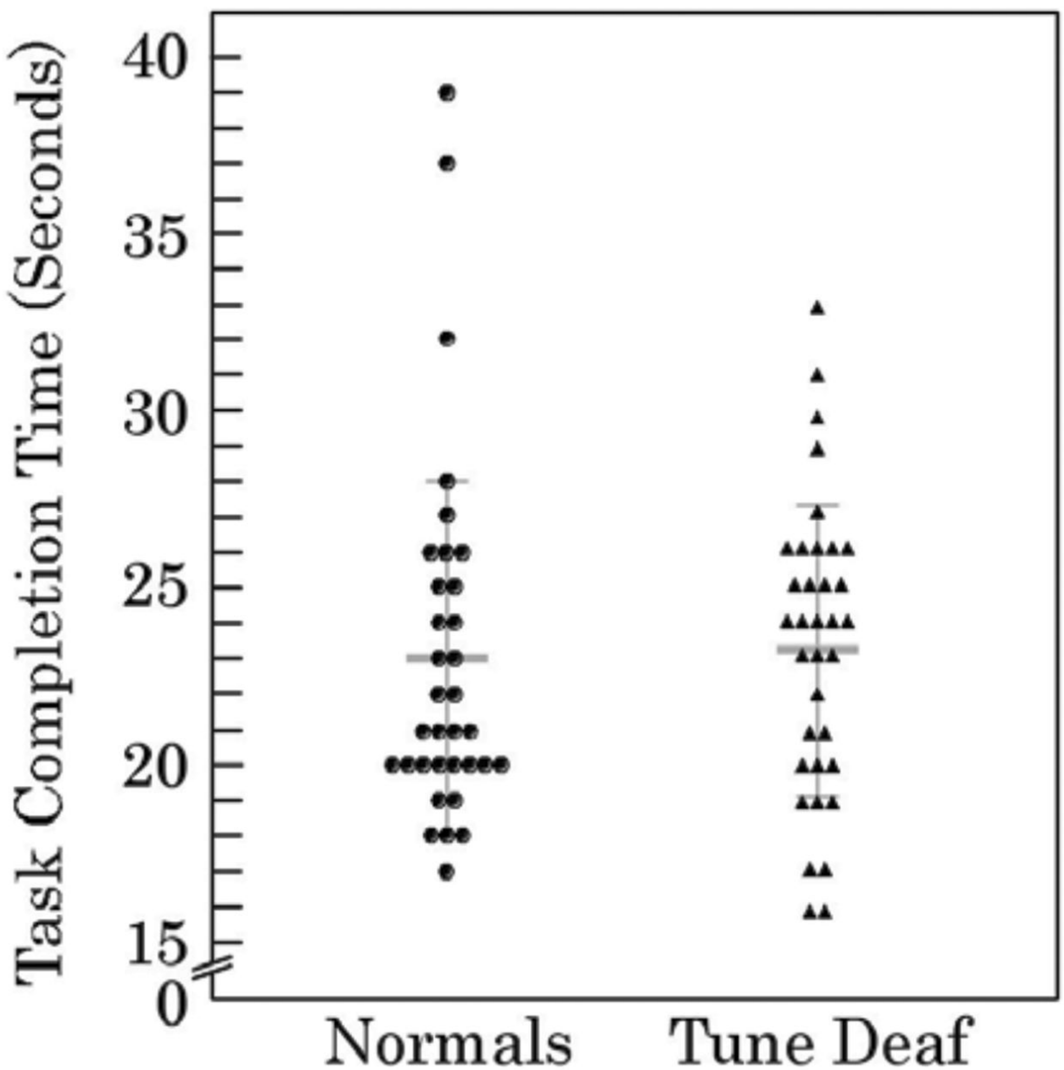

Number of Correct Responses
21
18
15
12
9
6
3
0
Normals
Tune Deaf
Number of Correct Responses
18
16
14
12
10
8
6
4
2
0
Normals
Tune Deaf

Figure 8.

Figure 8a. Performance of Normal and Tune Deaf Groups on Memory for Digits Subtest.
Figure 8b. Performance of Normal and Tune Deaf Groups on Nonword Repetition Subtest.


Task Completion Time (Seconds)
40
35
30
25
20
15
0
Normals
Tune Deaf

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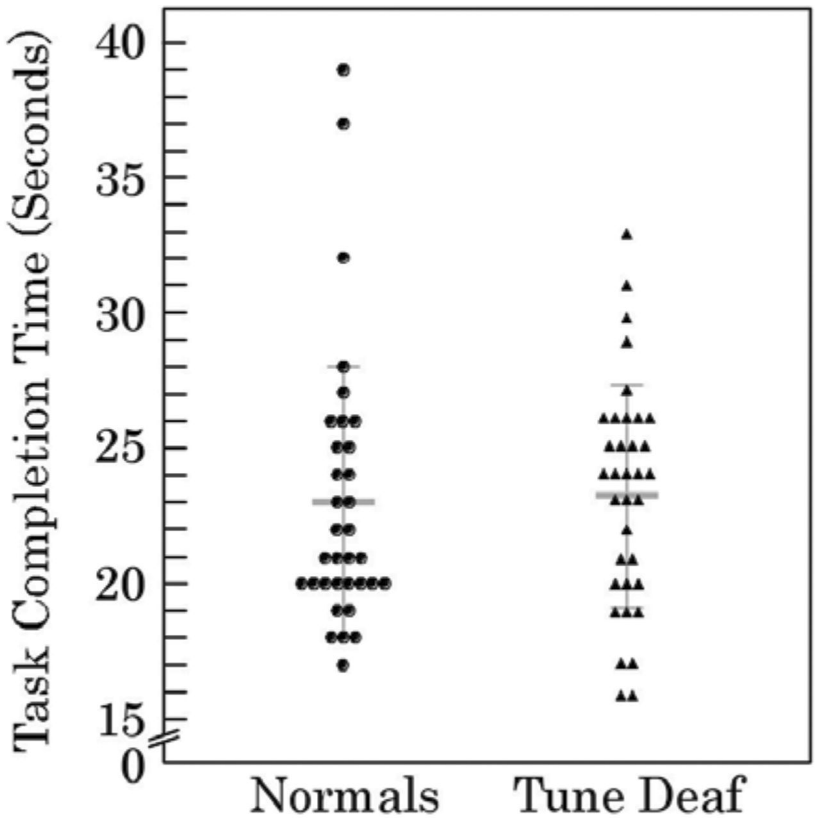

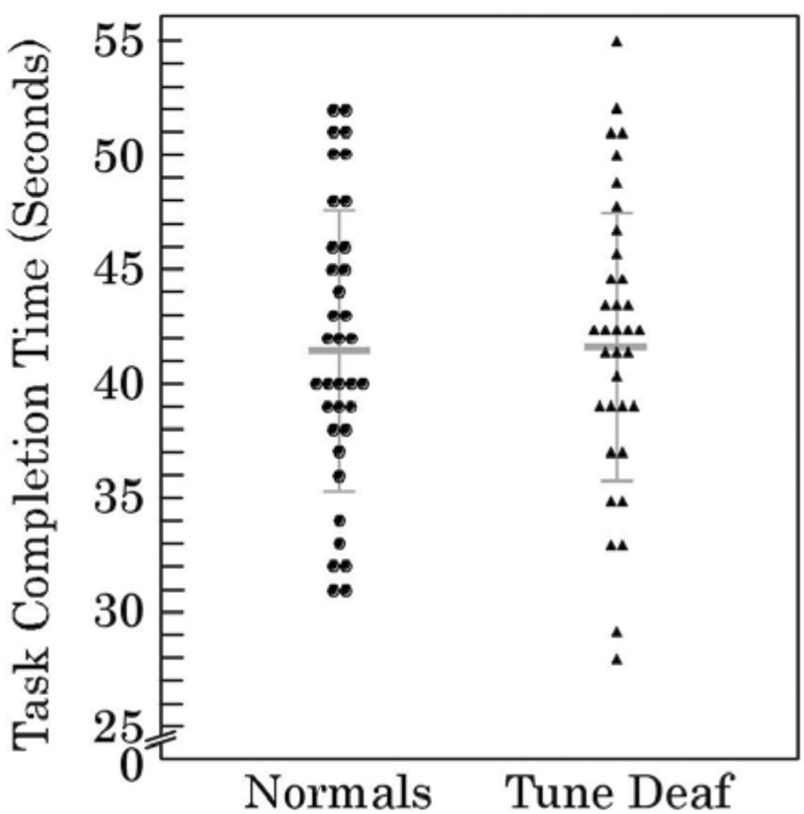

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Figure 9.

Figure 9a. Performance of Normal and Tune Deaf Groups on Rapid Digit Naming Subtest.
Figure 9b. Performance of Normal and Tune Deaf Groups on Rapid Letter Naming Subtest.
Figure 9c. Performance of Normal and Tune Deaf Groups on Rapid Object Naming Subtest.

Table 1

Demographics of Participants

Subjects	DTT Mean	Age Mean	Right Handed	Left Handed	Female	Male	Education
Normal Controls	25	27	30	4	17	17	15
Tune Deaf	16	25	30	5	21	14	14

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Table 2

Correlations between auditory processing tests in tune deaf individuals. Spearman Correlation Coefficients, N=35

		Pitch and auditory processing tests							Memory tests				
		DTT	**DLF**	**PPT-L**	**PPT-R**	**DPT-L**	**DPT-R**	**GIN, ms**	**MFD**	**NWR**	**RDN**	**RLN**	**RON**
Pitch and auditory processing tests	DTT	1.000											
	DLF	−.171	1.000										
	PPT-L	.091	−.088	1.000									
	PPT-R	.020	.078	.854	1.000								
	DPT-L	.070	−.096	.721	.630	1.000							
	DPT-R	−.020	−.118	.757	.755	.856	1.000						
	GIN, ms	−.032	−.194	.444	.352	.446	.498	1.000					
Memory tests	MFD	.197	−.094	.103	.044	.280	.230	.357	1.000				
	NWR	−.055	.047	.023	.054	.161	.146	.231	.286	1.000			
	RDN	−.030	.084	−.119	−.036	−.266	−.366	−.220	−.431	−.328	1.000		
	RLN	.144	−.155	.043	.065	.068	−.070	−.075	−.217	−.077	.339	1.000	
	RON	−.167	−.035	−.331	−.259	−.368	−.321	−.129	−.201	−.235	.236	.132	1.000