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TEMPORAL PROCESSING IN LISTENERS WITH UNILATERAL HEARING LOSS

by

Deborah K. Miller

A Capstone Project
submitted in partial fulfillment of the
requirements for the degree of:

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Abstract: Temporal processing is examined for sounds delivered to the intact ear of individuals with unilateral hearing, and delivered to one ear of individuals with normal, bilateral hearing. Two temporal processing skills are assessed: 1) the ability to detect sinusoidal amplitude modulation of a wide-band noise, for various modulation frequencies, and 2) the just-noticeable-difference for temporal complexity of random-spectrogram-sounds.

Acknowledgments

The author would like to acknowledge the unyielding guidance and support from Dr. Rosalie M. Uchanski and Dr. Jill B. Firszt. It is from you that I have gained the utmost respect for the commitment and passion for research. Thanks are also extended to Timothy Holden for writing the software to conduct this study, and to Brandi McKenzie for aiding in scheduling and recruitment of subjects. Additionally, the statistical analysis provided by Dorina Kallogjeri is greatly appreciated. Special thanks are given to Andrea O’Neil, Marcus Roque, Kathryn Goren, and Kathy and Eric Miller for their endless support and guidance throughout this process.

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ABBREVIATIONS

dB (HL)	decibel (hearing level)
dB (SPL)	decibel (sound pressure level)
f_m	modulation frequency
Hz	Hertz
JND	just noticeable difference
kHz	kilohertz
NH	normal hearing
RSS	random spectrogram sounds
SL	sensation level
TMTF	temporal modulation transfer function
UHL	unilateral hearing loss

INTRODUCTION

Asymmetric hearing leads to an imbalanced auditory input to the brain. One special case of asymmetric hearing is described by one ear with essentially normal hearing (NH) (audiometric thresholds ≤ to 25 dB HL) and the other ear with severe-to-profound hearing loss (thresholds ≥ 70 dB HL) (Cozad, 1977). This is sometimes categorized as unilateral hearing loss (UHL), though a strict definition of UHL has yet to be established. Some studies have explored the educational and social disadvantages of asymmetric auditory input (Lieu, 2004). Yet, focus has recently turned to listeners with UHL in order to explore the plasticity and capabilities of the auditory pathways in the brain with asymmetrical auditory input. It is a common assumption that the audiometrically normal ear of individuals with UHL perform as well as one ear of an individual with bilateral NH. However, little research has examined this assumption.

When listening with two normal hearing ears, there is well-documented evidence describing specific advantages for binaural hearing. These "binaural advantages" include: the head shadow effect, binaural summation, increased localization abilities, and the binaural squelch effect. The head shadow effect describes the approximate 6.4 dB decrease in level of a signal as it travels from one side of the head to the opposite side. The attenuation of the signal increases as the frequency of the signal exceeds 2000 Hz. Binaural summation is described as an increase in the perception of loudness when listening binaurally rather than monaurally. At levels close to threshold, the loudness sensation listening with one ear is equivalent to listening with two ears when the stimulus is reduced by 3 dB. At higher sensation levels (≥ 35 dB SL), the loudness sensation listening with one ear is equivalent to listening with two ears when the stimulus is reduced by 6 dB (Gelfand, 2007). Binaural listening also increases the ability to locate a sound source by utilizing interaural time and intensity differences between the two ears.

Lastly, binaural squelch, or the “cocktail party effect”, refers to the physiologic phenomenon allowing focus on a desired auditory signal in the presence of background noise. Interaural timing differences of the modulating envelope of the signals have been shown to be an integral aspect of this phenomenon (Ohlemiller, 2008).

Further evidence has shown that normal temporal resolution is an important aspect of pitch perception (Ohlemiller, 2008) and speech understanding (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995; Feng, Yin, Kiefte, & Wang, 2010). In human speech, slow modulations may convey different types of linguistic information. Segmental information relating to voicing and manner, and prosodic cues relative to intonation and stress may be obtained from modulation of speech in the range of 50 and 500 Hz. A recent analysis of the acoustic properties of vowels and diphthongs by Tsiakoulis & Potamianos (2009) found that amplitude modulation may also be related to speaker identification. In addition, an acoustical analysis of natural environmental sounds reveals most natural sounds have low temporal modulations, distinguishing them from white noise (Singh & Theunissen, 2003). Because temporal resolution plays such an integral part of everyday listening and aids in the extraction of important auditory information, it is fitting to extend investigations of temporal processing abilities to listeners with UHL.

Modulation Detection to Observe Temporal Resolution through the Temporal Modulation Transfer Function (TMTF)

To evaluate whether UHL listeners have similar temporal resolution abilities as NH listeners, well-established psychoacoustic temporal processing tasks can be employed. Common psychoacoustic tasks utilized in the evaluation of temporal resolution include the detection of gaps (‘gap detection’) or ‘amplitude modulation detection’. Gap detection reflects the shortest interval of silence a listener can detect, whereas amplitude detection reflects an individual’s ability to detect slow overall changes in the amplitude of a sound (Gelfand, 2007). Both methods are important in determining temporal resolution abilities, although amplitude modulation detection is often preferred due its ability to examine the effects of intensity resolution and temporal resolution independently (Strickland & Viemeister, 1997).

In amplitude modulation detection tasks, the modulation depth necessary to just notice the modulation of a sinusoidally amplitude modulated wide band noise (known as the “carrier”) is measured for numerous modulation frequencies. The temporal modulation transfer function (TMTF), a graph of amplitude modulation detection of as a function of frequency, allows a quantitative description of the temporal resolution ability of an individual (Viemeister, 1979). The TMTF plots the value of the modulation depth, m, that is just-detectable (termed “threshold”), typically expressed as $20\log m$, as a function of the frequency of modulation (f_m) (Viemeister, 1979). The modulation depth, or index, m, ranges between 0 and 1, where 0 refers to the noise carrier with no modulation and 1 refers to 100% modulation applied to the noise carrier. Poor resolution would be noted when a large modulation depth is required to detect the modulation of the noise carrier. For example, the poorest threshold one may obtain, $m = 1$ ($20\log m = 0$ dB), implies that 100% modulation is needed for the listener to discriminate an unmodulated noise (0% modulation) from the modulated noise. More typically, a small modulation depth may be adequate to detect the modulation (*e.g.*, $m=0.0563$, which is approximately 5% modulation, or $20\log m = -25$ dB). Thus, the smaller the modulation depth at threshold, the more negative the value of $20\log m$ plotted on the ordinate of the TMTF (Takahashi & Bacon, 1992; Viemeister, 1979).

TMTF of Normal Hearing Listeners

Previous studies have suggested that listeners with NH bilaterally have relatively good sensitivity to modulation at low modulation frequencies. Temporal resolution studies using TMTFs have revealed a fairly consistent shape, often described by a low-pass characteristic with a 3 dB cutoff frequency of approximately 50 Hz (Bacon & Gleitman, 1992; Bacon & Viemeister, 1985; Formby, 1985; Viemeister, 1979). Above the cutoff frequency of 50 Hz, detection of modulation appears to become progressively poorer at a rate of about 4 dB per octave (Bacon & Gleitman, 1992; Bacon & Viemeister, 1985; Formby, 1985; Viemeister, 1979). In general, the TMTF appears to be fairly independent of level (within 3 dB) for noise spectrum levels ranging between 0 and 50 dB SPL (Bacon & Viemeister, 1985; Viemeister, 1979; Bacon & Gleitman, 1992). A white noise carrier is often used in amplitude modulation detection experiments due to its consistent long-term amplitude spectrum, allowing confidence of an accurate reflection of temporal resolution (Moore & Glasberg, 2001). Sinusoidal carriers have also been used in TMTF experiments (Viemeister, 1979; Kohlrausch, Fassel, & Dau, 2000). In these experiments, the shape of the TMTF reveals a higher cutoff frequency between 100-120 Hz. Additionally, when high-frequency (*e.g.*, 10 kHz) sinusoidal carriers are used, a shallower slope may be observed below 100 Hz and a steeper slope is seen above 100 Hz (Kohlrausch, et al., 2000).

Results from previous psychoacoustic studies of temporal resolution abilities suggest that amplitude modulation detection abilities may be poorer in older adults than younger adults. Although, significant differences have yet to be found consistently. The same low-pass characteristic shape of the TMTF has been observed in both younger and older listeners with hearing loss as those found in studies of NH subjects (Bacon & Gleitman, 1992; Bacon &

Viemeister, 1985; Formby, 1987). A trend of increasing deterioration in thresholds as frequency of modulation increases has also been noted for older listeners (He, Mills, Ahlstrom, & Dubno, 2008). The trend of poorer modulation detection thresholds associated with aging may be confounded by high-frequency sensorineural hearing loss often present in older populations (Takahashi & Bacon, 1992).

TMTF of Listeners with Hearing Loss

Studies exploring temporal resolution in individuals with hearing loss have uncovered deficits in sensitivity to amplitude modulation. The degree of deficit observed appears to be dependent on the configuration of the hearing loss (Bacon & Viemeister, 1985; Formby, 1987). TMTFs of listeners with high frequency sensorineural hearing loss show poorer overall modulation detection thresholds when utilizing either broadband noise carriers (Bacon & Viemeister, 1985) or tonal carriers (Moore & Glasberg, 2001). Attenuation rates as great as 10.1 dB per octave have been documented (Bacon & Viemeister, 1985). Furthermore, higher frequency modulation detection thresholds tend to be worse than those of lower frequency modulations (Bacon & Viemeister, 1985; Formby 1987).

In individuals with high-frequency hearing loss, decreased temporal resolution has been explained by the effects of level and frequency region of the signal. In 2000, Strickland described effects consistent with those found by Bacon and Viemeister in 1985. Strickland stated:

> Temporal resolution is limited by frequency region at low levels, but little if at all at higher levels. This suggests that for broadband signals, such as speech, at high levels the amplitude envelope may be equally well represented across frequency regions. For lower levels, the representation of the envelope will certainly vary across frequency regions. If listeners are restricted to the lower frequency regions due to damage to higher frequency regions, their temporal resolution will be poorer.

Although research has revealed reduced resolution abilities in those with hearing loss, results may have been compromised by the limited audibility of the stimuli in these studies (Moore, Shailer, & Schooneveldt, 1992; Bacon & Gleitman, 1992). The decreased dynamic range of listeners with hearing loss may limit the ability to assess such listeners at adequate sensation levels (SL) needed to measure modulation sensitivity accurately (Moore et al., 1992). When modulation detection thresholds were obtained for listeners with flat hearing loss, using broadband noise (Bacon & Opie, 2002) or using tonal carriers at equal SPL or SL (Bacon & Gleitman, 1992), thresholds were not significantly different from those of NH listeners. When normal hearing listeners were examined with a low-pass filter and high-pass noise masker to simulate a narrower listening bandwidth, as seen in high-frequency hearing loss, the subjects with high-frequency hearing loss had similar TMTFs to the NH subjects (Bacon & Viemeister, 1985). Temporal resolution abilities in participants with cochlear hearing losses were found to be similar in those with normal hearing when examined at equal SPL or SL (Moore et al., 1992).

In 1987, Formby compared the “better ear” of individuals with unilateral hearing loss to their “poorer ear”, which had hearing loss due to Ménière’s disease. Modulation thresholds found the in poorer ears tended to be similar to the better ears between 60-100 Hz, but declined in sensitivity at higher modulation frequencies. This decline was found to be about 6 dB per octave, noted as approximately twice the attenuation rate found for normal ears. However, extreme asymmetry in hearing was not observed in the subjects, as audiometric thresholds of the “poorer ears” of the participants spanned a large range, between 25 and 80 dB HL, and hearing thresholds in the “better ears” were not consistently within ≤ 25 dB HL. Contrary to the idea that decreased performance may be caused by limited audibility, deteriorated performance in temporal resolution tasks have been identified in specific listeners with high-frequency sensorineural hearing loss when tested in low frequency regions, where the individuals had normal audiometric sensitivity (Feng et al., 2010). In general, findings are inconsistent regarding temporal resolution in listeners with hearing loss.

Psychoacoustic Abilities of Listeners with Unilateral Hearing Loss

To date, Sininger and de Bode (2008) have published the only psychoacoustic study of temporal processing in the good ear of listeners with UHL. Using a gap detection threshold paradigm, no significant differences in temporal resolution abilities were found between subjects with NH bilaterally and those with UHL. In addition, when comparing those with congenital UHL to the corresponding ear of NH listeners, no differences were found between the two groups. A recent study by Firszt, Uchanski, Burton & Reeder in 2010 (submitted for publication) utilizing Random Spectrogram Sound (RSS) stimuli (Schönwiesner, Rubsamen, & von Cramon, 2005) found that listeners with UHL performed more poorly than listeners with bilateral NH (when restricted to listening monaurally) on tasks varying in temporal complexity. The RSS stimuli may be useful in psychoacoustic experiments to explore sensitivity to spectral or temporal complexity independent of one another. Using an adaptive procedure, just-noticeable-differences (JNDs) of the temporal modulation rate in RSS stimuli were obtained.

Although differences were seen between the NH and UHL subject groups, RSS stimuli are novel, and JND performance with these stimuli is not easily converted to other measures of temporal processing. Therefore, this capstone project is an extension of the Firszt et al. study. In this project, the temporal processing abilities of individuals with UHL will be addressed using RSS stimuli and using a more traditional method, the temporal modulation transfer function. Essentially two separate psychoacoustic experiments were employed. The first aim was to examine the common assumption of similar performance in listeners with UHL and listeners with NH, restricted to listening monaurally for an amplitude modulation detection task. Second, the same assumption was investigated for a just-noticeable-difference task with RSS stimuli only varying in temporal complexity.

METHODS

Subjects

Two groups of listeners participated in these experiments, listeners with unilateral hearing loss (UHL) and listeners with normal hearing (NH). Seven UHL participants were recruited from the Washington University School of Medicine Department of Otolaryngology. Then, seven NH participants were recruited from the Volunteers for Health database, to match each UHL participant in gender and age, within 5 years. All listeners were monetarily compensated for their participation. The UHL subjects ranged in age from 32 to 60 years (3 females, mean = 49, and 4 males, mean = 47) and the NH subjects ranged in age from 28 to 62 years (3 females, mean = 49, 4 males, mean = 46). All seven of the UHL participants and one of the NH participants had previous experience with the RSS stimuli through participation in on ongoing study by Firszt et al. (2010). Participants attended two test sessions of approximately two hours each, over the course of a 2-3 week period. During each session participants were provided breaks, as needed, to reduce the effects of boredom and fatigue.

Hearing screenings were performed for all participants. Using a Grason-Stadler GSI-61 audiometer, ear specific pure-tone air conduction thresholds were measured at octave frequencies between 250 and 8000 Hz. All testing was performed through Etymotic Research ER-3A insert phones in a double-walled sound attenuating booth.

Participants with hearing thresholds ≤ 25 dB HL in each ear were included in the NH subject group. Participants were included in the UHL subject group if the hearing thresholds in their better ear were ≤ 25 dB HL and if the hearing thresholds in their poorer hearing ear were ≥ 70 dB HL when the better ear was effectively masked with narrowband noise. Detailed subject information can be found in APPENDICES A and B.

During experimental testing, the stimuli were presented monaurally via insert phones to all participants. For UHL participants, the stimuli were presented in the "intact" ear while the "poorer" non-test ear was left open. For the NH participants, the side of presentation was the same as their UHL age and gender match. The non-test ears of the NH subjects were blocked from receiving ambient sounds through the combined use of an EAR EarSoft FX UF foam ear-plug and a Howard Leight Thunder 29 sound attenuating ear-muff.

Amplitude Modulation Detection Thresholds

Stimuli

All sound stimuli were digitally generated, a priori, using MATLAB software and their presentation during the experiment was controlled by a personal computer. A 24-bit D to A converter was utilized. The modulated *target* signal (simple amplitude modulation of wide-band noise by a sine wave) was defined as

$$\boldsymbol{T(t)} = c[1 + m\ \sin[(2\pi f_m]t + \varphi_m)]n(t)$$

where *c* is a multiplicative scalar for normalizing power in *T(t)* to match that of *n(t)*

$$c = \left[1 + {m^2}/{2}\right]^{-0.5}$$

and, *n(t)* is a wide-band noise with bandwidth from 0 to 10,000 Hz (the carrier); *m* is the modulation depth (values range from 0 to 1); f_m is the modulation frequency; and φ_m is the starting phase of the modulation signal randomly chosen with a uniform distribution [0-2π] for each target. The *standard* signal consisted of only the wide-band noise, *n(t)*. The wide-band noise, used for both *standard* and *target* signals, was created by generating spectral magnitude components with random amplitudes specified by a Rayleigh distribution and with random phases specified by a uniform distribution [-π, +π]. For the *target* signals, the starting phase, φ_m, of the modulating signal was chosen randomly for each *'target'* interval in every trial. To smooth the onsets and offsets of the stimuli, a 20 ms raised-cosine gating was applied to each stimulus. The sampling frequency was 44100 Hz.

The signals in each interval (*standard [unmodulated]* or *target [modulated]*) were based on independent noise samples. Each signal was normalized to the same overall power, and then a random rove in level was applied to each interval, using a uniform distribution of integers from -5 to +5 dB (Forest & Green, 1987; Stellmack, Viemeister, & Byrne, 2005). The overall presentation level was calibrated to have a median level of 60 dB SPL.

Five different modulation frequencies were used as target signals: 3, 9, 30, 90 and 300 Hz. In psychoacoustic tasks that utilize various modulation rates, research has shown that modulation detection abilities are limited by amplitude resolution for rates that are lower than approximately 16 Hz. For modulation rates generally above 16 Hz, modulation detection abilities tend to rely on temporal resolution abilities. Listeners with normal hearing have been shown to have decreased sensitivity to amplitude modulation as the frequency of modulation increases (Moore, 1998; Rosen, 1992). The modulation frequencies used in the present experiment span both above and below 16 Hz. Although the sinusoidal correlates (when represented as pure-tones) of modulation frequencies such as 3 and 9 Hz are obviously below the threshold of human hearing, such modulation rates are identified through the neurophysiologic temporal coding mechanism of the auditory system (Ohlemiller, 2008). These low modulation rates are studied due to their important assistance in the classification of acoustic stimuli (Rosen, 1992).

Procedures

Modulation detection thresholds were obtained utilizing an adaptive three-interval, three-alternative forced-choice procedure with a 3-down, 1-up rule that yields a modulation depth, *m*, that corresponds to 79.4% correct detection of modulation (Levitt, 1971). The modulation depth that is just detectable (at threshold) was determined for five different modulation frequencies: 3, 9, 30, 90 and 300 Hz.

Participants were presented with three, 1 second intervals per trial. Two of the three intervals contained an unmodulated (*standard)* wide-band noise, and one interval contained a sinsuoidally amplitude modulated wide-band noise. All intervals were presented in random order and were separated by 500 ms inter-stimulus intervals of silence. Initially, the modulation depth, *m*, was relatively large (m = 0.4) and *m* decreased adaptively as the listener responded correctly.

Initiation of each block of trials was controlled by the participant. Each trial was accompanied by a light indicator on the computer monitor in front of the subject. Using the touch-sensitive computer monitor, the subject selected his/her choice of “which one was different” (the target signal) of three intervals presented. Participants received visual feedback only after trials for which they responded correctly.

The modulation frequency (f_m) of the target signal was fixed within a block of trials and modulation depth was adapted (in units of $20\log m$), to obtain a modulation detection threshold or just-noticeable-difference between unmodulated signals and amplitude-modulated signals. The initial modulation depth of the target signal was -8 dB. After three consecutive correct responses, the modulation depth changed by an initial step-size of 4 dB. For example, the initial decrease in *m* would change *log* modulation depth from -8 dB to -12 dB. If there was one incorrect response, *m* would increase therefore changing the modulation depth from -8 dB to -4dB. The step-size was not constant, and decreased to a 2-dB step-size after three reversals. A reversal is defined as a change in direction, increasing to decreasing or vice versa, of the adapting modulation depth. The block ended after 8 reversals were obtained. The mean of the last 6 reversals was calculated to obtain a mean for that block of trials. For f_m = 300 Hz only, the initial modulation depth was changed to -2 dB due to a floor effect found when the initial modulation depth was -8 dB.

During the first test session, each participant completed one practice block for each f_m, followed by a short break, and then completed one test block for each f_m. During the second test session modulation detection thresholds were obtained for each f_m followed by a short break, and then were acquired again. All f_m blocks were presented in random order. For each subject, the average modulation depth of the three blocks, for each f_m, was calculated as the amplitude modulation detection threshold.

Random Spectrogram Sound (RSS) Just-Noticeable-Difference (JND)

Stimuli

The RSS stimuli were generated with the MATLAB software package on a personal computer using scripts developed by Schönwiesner et al. (2005). To create an RSS stimulus, a spectrographic grid of random amplitude levels is created with specified temporal and spectral characteristics; one number for each tile in the spectrographic grid. Pure tones are also generated, and are multiplied by their appropriate spectrographic amplitude levels to produce a set of amplitude-adjusted pure tones. Then, the amplitude-adjusted tones are summed to create a single stimulus. The abscissa of the grid controls the temporal modulation rate (or temporal change rate in Hz). The ordinate determines the number of spectral regions, and covers a 6-octave range from 250 to 16 kHz. Each spectral region had the same equivalent rectangular bandwidth (ERB), corresponding to regions of roughly equal frequency resolution in human audition (Moore & Glasberg, 1983), and a total of 1638 pure tones were used across this 6-octave range. For both the *RSS target* and *RSS standard* stimuli, the number of spectral components was fixed at three. The frequency ranges for the spectral regions were as follows: 250-1319 Hz, 1322-4793 Hz, and 4793-16000 Hz. The *RSS standard* contained a constant temporal modulation rate of 30 Hz, whereas the *RSS target* stimulus had a temporal modulation rate that was adapted. The duration of all the stimuli was 4 sec. The resulting stimulus contained an average power spectrum approximating pink noise due to its considerably logarithmic function. Further detail and visual representation of the stimuli can be found in Schönwiesner et al. (2005).

Procedures

Procedures for obtaining the temporal RSS JND were based on those used in Firszt et al. (2010). Similar to the modulation detection experiment, an adaptive three-interval, three-alternative forced-choice procedure (Levitt, 1971) was employed to determine the JND for RSS which varied only in temporal complexity (i.e., temporal modulation rate).

Subjects were presented with three, four-second intervals per trial, two of which randomly contained the RSS with a constant temporal change rate (TCR) of 30 Hz (*RSS standard*). The third interval contained the RSS signal with an adapted TCR (*RSS target*). The participants controlled the start of each run. The order of presentation of the intervals of RSS *standard* signals and the RSS *target* signal were randomized for presentation within a session for each subject. A light indicator on a touch-sensitive computer monitor mounted in front of the subject illuminated with each trial. The subject selected the interval they believed to contain the target signal and obtained immediate visual correct response feedback. After the listener correctly responded three times consecutively, the TCR increased from an initial 8 Hz TCR to 14 Hz (step size = 6 Hz). This step-size was used until an error occurred. After the first reversal, the step-size decreased to 3 Hz. After the listener responded with a second set of three consecutive correct answers, the step-size decreased to 1 Hz. The run ended after 6 reversals were obtained. The mean of the TCR at the last 4 reversals was calculated for that run. One training run was conducted, followed by three test runs. Each run was presented randomly either before or after the modulation detection threshold experiments. The temporal RSS JND was calculated, with respect to the *standard* RSS stimulus with its TCR of 30 Hz. For example, if the mean of the TCRs for the three test runs is 25 Hz, then the temporal RSS JND would be 30-25, or 5 Hz.

RESULTS

Amplitude Modulation Detection Thresholds

Average amplitude modulation detection thresholds over three test sessions for the NH and UHL subject groups are expressed as *20log m* and are plotted as a function of modulation frequency. The TMTFs seen in FIGURE 1 indicate better performance toward the top of the graph, as threshold values become more negative. Poorer temporal resolution is seen as thresholds fall lower on the graph, as values become more positive. Subjects with UHL are represented as solid squares and subjects with NH are represented by open circles. All error bars represent the 95% confidence interval for the mean.

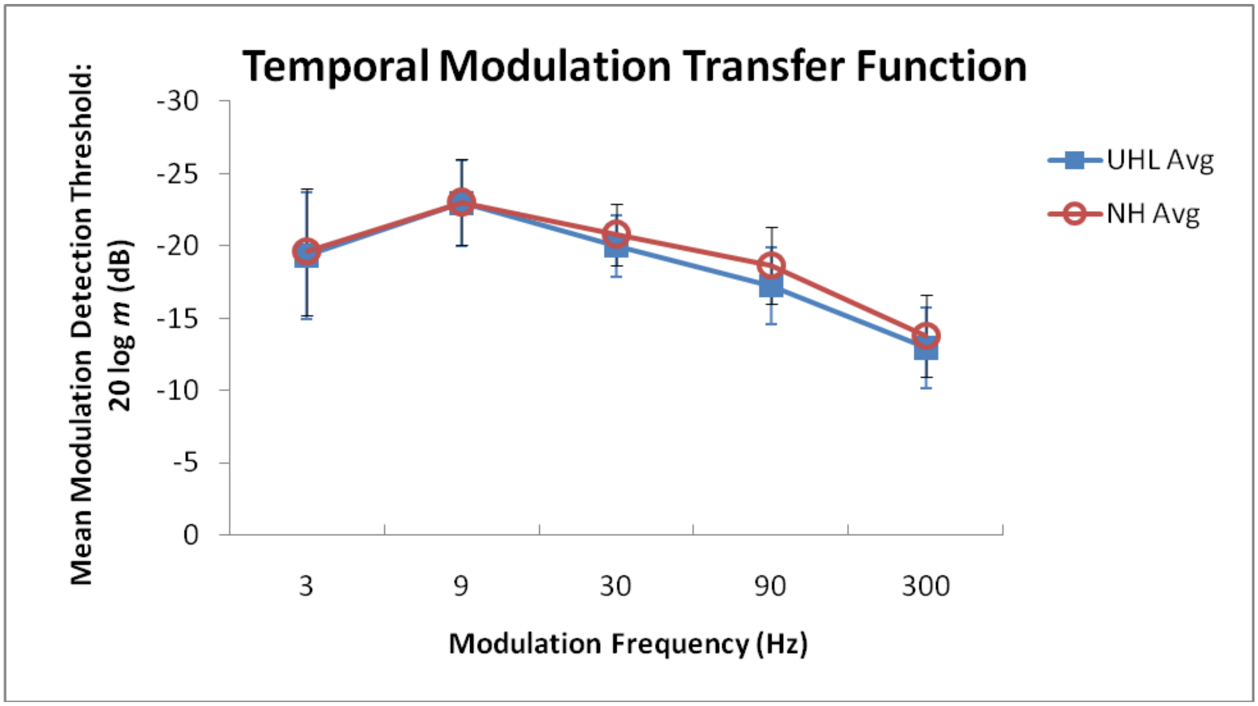

FIGURE 1. Temporal modulation transfer function (TMTF) conveying mean amplitude modulation detection thresholds with a wide band noise carrier expressed as 20log *m*, where *m* is the modulation index, plotted as a function of frequency of modulation (f_m). Average threhold results of three test sessions are displayed from the better ear of seven subjects with UHL and seven NH subjects matched for age, gender, and ear-tested. Error bars show the 95% confidence interval for the mean. No significant difference is observed between NH and UHL subject groups across modulation frequencies tested.

A mixed between-within analysis of variance was performed for data, with main factors of subject group (between) and test session (repeated-measures within). Each modulation frequency was analyzed independently. No statistically significant main effect of subject group was found, at any modulation frequency. In addition, no statistically significant main effect was found for test session, for four of the five modulation frequencies. For the 9 Hz modulation frequency, a main effect of test session was found [F92, 24) = 3.95, p = 0.033]. Due to a small effect size, Bonferroni corrected post hoc tests were unable to identify which test sessions were significantly different from the others. A second, larger mixed between-within analysis of variance was conducted in which modulation frequency was treated as another factor. This analysis revealed no significant main effect of subject group [F(1,12)=0.16. p=0.696] or test session [F(2,24)=2.29, p=0.123]. Also, none of the interactions (both 2-way and 3-way interactions) were statistically significant. However, there was a significant main effect of modulation frequency. The F statistic from the Green-House-Geisser test was utilized because the Mauchly's test of sphericity was significant [F(2.2, 48) = 38.5, p < 0.001]. Bonferroni corrected post hoc tests further identified significant differences among specific modulation frequencies. The average detection threshold for f_m = 3 Hz (mean ± SE = -19.5 ± 1.4) was not statistically different from the average threshold for f_m = 30 Hz (mean ± SE= -20.4 ± 0.69) or for f_m = 90 Hz (mean ± SE= -18.0 ± 0.85), but was significantly different from average thresholds for f_m = 9 Hz (mean ± SE= -23.0 ± 0.96) and f_m = 300 Hz (mean ±SE= -13.4 ± 0.91). Average thresholds for f_m = 9 Hz were significantly better than those at all other frequencies, and thresholds at f_m = 300 Hz were significantly poorer than those at all other modulation frequencies. For f_m = 30 Hz and f_m = 90 Hz, average detection thresholds were significantly different from those at all other modulation frequencies except $f_m = 3$ Hz. See TABLE 1 for specific statistical results.

Random Spectrogram Sound (RSS) Stimuli Just-Noticeable-Difference (JND)

FIGURE 2 displays the mean RSS temporal JNDs (re: 30 Hz) for three test sessions plotted as a function of subject group. Mean JND is represented for subjects with UHL by the solid square, whereas the mean JND for subjects with NH corresponds to the open circle. Error bars indicate the 95% confidence interval of the mean. Data points lower on the graph indicate better temporal complexity detection ability than those higher on the graph.

To compare the performance of UHL subjects with that of NH subjects, a mixed between-within subjects analysis of variance was performed for data from three test sessions for each subject. No statistically significant main effect was found for subject group, and no significant interaction was observed for subject group by test session [$F(2, 24) = 1.05$, $p = 0.37$].

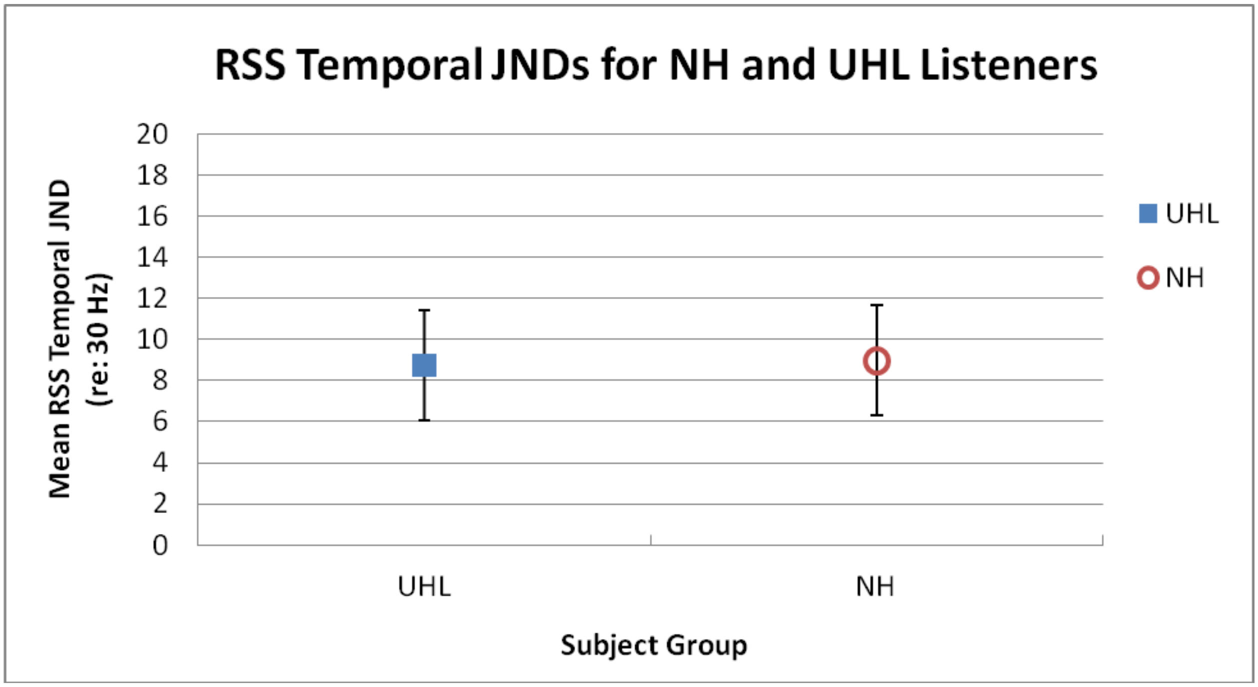

FIGURE 2. Mean just-noticable-differences for subject groups, averaged over three test sessions, utilizing random spectrogram sounds (RSS) varying in temporal complexity (re: 30 Hz) are plotted by subject group from the better ear of seven subjects with UHL and NH age and gender matched subjects restricted to listening with the corresponding ear. Error bars show the 95% confidence interval of the mean. No statistically significant difference was found for subject group.

However, a significant main effect of test session was observed [F(2, 24) = 4.71, p = 0.019], and this is effect shown in FIGURE 3. Bonferroni corrected post hoc tests were unable to identify which test sessions were significantly different from the others due to limitations of a small effect size. Specific statistical results can be found in TABLE 1.

		Modulation Frequency (Hz)				
	RSS	**3**	**9**	**30**	**90**	**300**
Effect of Group	F(1,12) = 0.02, p = 0.894	F(1,12) = 0.01, p = 0.924	F(1,12) = 0.002, p = 0.969	F(1,12) = 0.36, p = 0.560	F(1,12) = 0.69, p = 0.423	F(1,12) = 0.21, p = 0.654
Effect of Session	F(2, 24) = 4.71, p = 0.019	F(2,24) = 0.34, p = 0.718	F(2,24) = 3.95, p = 0.033*	F(2,24) = 0.51, p = 0.605	F(2,24) = 0.98, p = 0.389	F(2,24) = 0.32, p = 0.733
Interaction of Group & Session	F(2,24) = 1.05, p = 0.37*	F(2,24) = 0.39, p = 0.676	F(2,24) = 18.81, p = 0.186	F(2,24) = 1.24, p = 0.306	F(2,24) = 3.25, p = 0.056	F(2,24) = 1.73, p = 0.199

TABLE 1. Statistical results for mixed between-within subjects analysis of variance for temporal modulation detection and RSS temporal JND tasks. *Statistically significant main effect of session found for f_m = 9 Hz and RSS temporal JND, although efforts to identify the specific test sessions of interest were inconclusive.

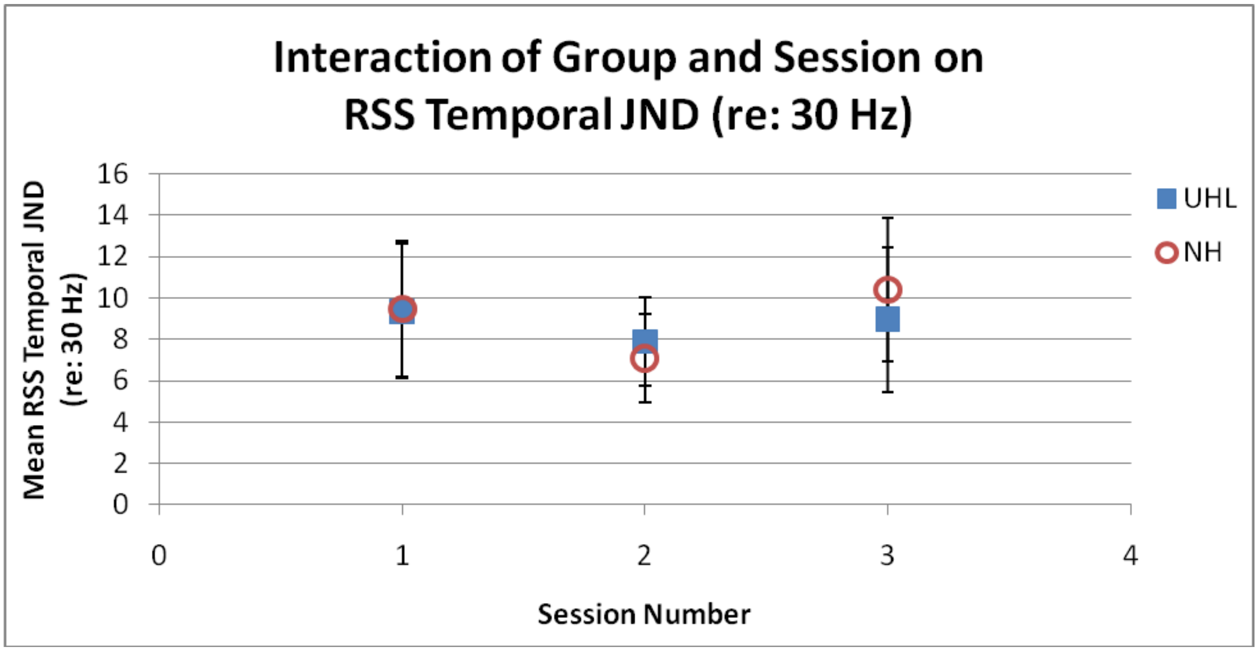

FIGURE 3. Mean RSS temporal JNDs (re: 30 Hz) for listeners with UHL tested in the better ear with age and gender matched listeners with NH (restricted to listening from the corresponding ear). Error bars show 95% confidence interval for the mean. No significant interaction of group and session is observed.

DISCUSSION

Data for the fourteen participants are shown in FIGURE 1 displaying the TMTFs for both UHL and NH listeners. The shape of both TMTFs are consistent with those found in previous studies for normal hearing listeners. The overall shape of the curve appears to contain a low-pass characteristic with a cutoff frequency consistent with those found in previous experiments utilizing noise carriers (Bacon & Gleitman, 1992; Bacon & Viemeister, 1985; Formby, 1985; Viemeister, 1979). Thresholds show an approximate attenuation rate of 2 dB per octave for both subject groups above the cutoff frequency, which is less steep than reported by others (Bacon & Viemeister, 1985). The TMTF for listeners with UHL is not significantly different than that for the NH subject group. These data are consistent with findings from UHL subjects tested by Sininger and de Bode (2008) who, utilizing gap detection measures of temporal resolution also found no significant differences between UHL listeners tested in their better ear and NH listeners restricted to listening monaurally.

For the second psychoacoustic measure of temporal processing no statistically significant difference between subject groups was observed for the JND task utilizing RSS stimuli (data shown in Figure 2). Mean RSS temporal JNDs found in this experiment were similar to those observed by Firszt et al. (2010) for the NH subject group. However, contrary to observations by Firszt et al., mean data obtained for the UHL subjects in the present study were not significantly different than those for the NH subject group. A significant main effect of session was also observed in the present data. However, the small subject pool available in the current study may have resulted in the inability to determine the exact session in question.

Data from the present study of mean RSS temporal JNDs were compared to the NH and UHL subject groups in the Firszt et al. (2010) study, which were both larger in size than the present study. The mean JND of the present NH subjects were found to be similar to the extreme ends of the data range of the Firszt et al. NH subjects. However, the average NH group means for the two studies are very similar. Individual means of listeners with UHL in the present study fell within the range of data collected by the larger sample from Firszt et al. (2005), but were more similar to the better performance end of the range. The variability in the present data emphasizes the need for a larger sample size to make a more thorough comparison between the studies.

From the results obtained in the current study, it appears that monaural auditory input from unilateral hearing loss does not affect temporal processing abilities as assessed by amplitude modulation detection thresholds or just-noticeable-differences in temporal complexity of RSS stimuli. Correlations were computed between these two psychoacoustic measures of temporal resolution: amplitude modulation detection thresholds and measures of JNDs using RSS stimuli varying in temporal complexity. A moderate correlation (r = 0.62) was observed between modulation detection performance and RSS temporal complexity JNDs, when all data are considered together (see FIGURE 4). A numerical display of all correlations can be found in APPENDIX C.

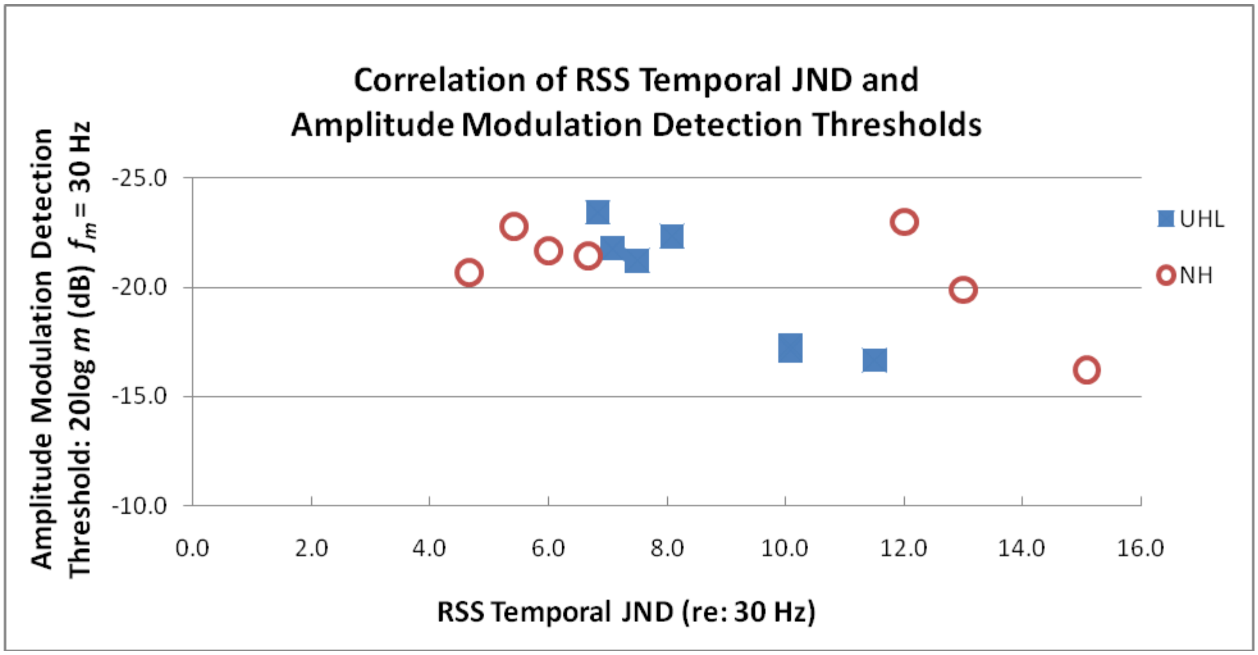

FIGURE 4. Average of the mean amplitude modulation detection thresholds for f_m = 30 Hz, in 20log *m* (in dB) are plotted by mean RSS temporal JND (re: 30 Hz) for both UHL and NH subject groups matched in age, gender, and ear of presentation. A correlation of 0.62 was observed between performances in the two types of psychoacoustic tasks.

Although exact physiologic mechanisms responsible for temporal resolution are still unclear, studies such as those by Bacon & Opie (1994) and Yost & Sheft, 1990 have suggested that processing is based more centrally than peripherally. They surmise this central processing location because of perceptual results that indicate amplitude modulation processing in one spectral region can be disrupted by introducing amplitude modulation in a different spectral region in the opposite ear. The results in this study support those found by Sininger and de Bode (2008) suggesting that processing of sound stimuli at the intact ear of those with unilateral hearing loss is similar to that found in the corresponding ear of normal hearing listeners when listening with monaural input.

Limitations to the current study include a skewed level of experience with the RSS temporal JND task. All participants in the UHL subject group were experienced with the task due to their previous participation in the Firszt et al. study (2010) utilizing the same stimuli, whereas the stimuli and task were novel to nearly all participants in the NH subject group. Due to a small sample size, data may sway heavily toward outlier performance. Further studies should utilize a larger sample size for a more thorough statistical analysis. Target populations for further studies should include a target population previously unexposed to the stimuli, in which the variability of experience would be eliminated.

CONCLUSION

The findings in this study suggest that subjects with unilateral hearing loss, when tested in the better ear, have modulation detection thresholds similar to those of normal hearing subjects, who are age and gender matched, when restricted to listening with a corresponding ear. Performance on a just-noticeable-difference in temporal complexity task using RSS stimuli also revealed no significant differences in performance between the two subject groups. Moderate correlations between RSS temporal JNDs and modulation detection thresholds were observed. Further psychoacoustic research is needed to fully understand the temporal processing abilities of individuals with unilateral hearing loss. More specific examinations utilizing RSS stimuli are warranted to better understand the applications of these novel stimuli in temporal processing experiments.

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APPENDIX A

Subject Demographics and Audiometric Thresholds

Subject	Sex	Age	Ear	Audiometric Thresholds (dB HL)							
				250 Hz	500 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz	8000 Hz
UHL1	F	52	LE	15	15	15	15	15	15	20	25
			RE	NR	NR	NR	NR	NR	NR	NR	NR
UHL2	M	58	LE	10	10	10	20	25	25	25	25
			RE	NR	NR	NR	NR	NR	NR	NR	NR
UHL3	F	47	LE	NR	NR	90	NR	NR	NR	NR	NR
			RE	15	15	10	0	0	5	0	5
UHL4	F	49	LE	95	NR	105	NR	NR	NR	NR	NR
			RE	25	25	25	15	10	20	20	25
UHL5	M	38	LE	NR	NR	NR	NR	NR	NR	100	NR
			RE	10	20	20	20	20	10	15	15
UHL6	M	32	LE	NR	NR	NR	NR	NR	NR	NR	NR
			RE	5	5	0	5	10	5	5	5
UHL7	M	60	LE	NR	NR	NR	NR	NR	NR	NR	NR
			RE	0	5	5	10	5	10	25	25
NH1	F	51	LE	5	5	10	15	10	10	10	5
			RE	10	5	10	15	5	15	15	10
NH2	M	55	LE	15	15	15	25	20	25	20	20
			RE	10	15	15	20	15	15	20	5
NH3	F	47	LE	20	15	10	10	20	25	25	20
			RE	15	15	20	10	15	15	20	15
NH4	F	49	LE	0	5	20	10	15	15	25	25
			RE	5	5	5	10	15	15	15	20
NH5	M	40	LE	5	0	5	10	5	15	15	15
			RE	5	5	10	5	10	15	10	10
NH6	M	28	LE	0	5	5	5	15	15	5	5
			RE	0	5	5	5	5	10	5	5
NH7	M	62	LE	10	10	10	15	10	10	5	10
			RE	15	15	10	10	25	15	10	10

Audiometric data for all subjects. Effective masking in the contralateral ear utilized when appropriate. LE = Left ear; RE = Right ear; NR = no response at the limit of audiometer.

APPENDIX B

Specific Cause of Hearing Loss for UHL Subjects

Cause of Unilateral Hearing Loss Per Subject	
Subject	**Cause of UHL**
UHL1	Right Side Acoustic Neuroma Removed (2005)
UHL2	Right Side Acoustic Neuroma Removed (1985)
UHL3	Left Side Sudden Hearing Loss (approx. 1990)
UHL4	Left Side Congenital Deafness of Unknown Cause
UHL5	Left Side Congenital or Early Childhood Deafness of Unknown Cause
UHL6	Left Side Permanent Hearing Loss From Fluctuating Hearing Loss (2006)
UHL7	Left Side Acoustic Neuroma Removed (2008)*

*Note UHL7 wears a bone conduction hearing device on the left side. The hearing device was not activated during testing.

APPENDIX C

Numerical Display of Average RSS Temporal JNDs and Amplitude Modulation Detection Thresholds

		Amplitude Modulation Detection Thresholds (mean *m* in dB) Averaged Over 3 Test Sessions Modulation Frequency (Hz)					
Subject	**RSS Avg Threshold**	**3**	**9**	**30**	**90**	**300**	**Across Frequency Avg**
UHL1	11.50	-13.11	-17.78	-16.67	-12.11	-9.11	-13.76
UHL2	8.08	-25.55	-25.11	-22.33	-18.44	-12.78	-20.84
UHL3	10.08	-19.89	-21.67	-17.33	-15.89	-16.89	-18.33
UHL4	10.08	-7.00	-17.22	-17.11	-13.00	-7.56	-12.38
UHL5	6.83	-25.55	-29.00	-23.44	-21.67	-16.22	-23.18
UHL6	7.50	-22.54	-23.89	-21.22	-19.67	-14.44	-20.35
UHL7	7.08	-21.78	-26.00	-21.78	-19.89	-13.56	-20.60
UHL Correlations with RSS		0.76	0.91	0.95	0.97	0.57	0.88
NH1	6.67	-19.33	-21.78	-21.44	-17.89	-18.67	-19.82
NH2	6.00	-22.78	-27.00	-21.67	-18.33	-13.22	-20.60
NH3	13.00	-19.78	-22.67	-19.89	-17.67	-8.67	-17.73
NH4	5.42	-22.33	-24.34	-22.78	-22.78	-14.00	-21.25
NH5	15.08	-13.78	-18.33	-16.22	-14.21	-12.22	-14.95
NH6	4.67	-18.11	-22.78	-20.67	-20.00	-17.11	-19.73
NH7	12.00	-21.22	-24.22	-23.00	-19.67	-12.56	-20.13
NH Correlations with RSS		0.54	0.57	0.61	0.69	0.70	0.81
Combined UHL & NH Correlations with RSS		0.47	0.58	0.62	0.65	0.59	0.64

Individual data for all fourteen subjects. The mean of three test sessions is shown for each subject for the RSS temporal JND task and amplitude modulation detection tasks for f_m = 3, 9, 30, 90, and 300 Hz. The Across Frequency Mean column exhibits the mean of the data points listed for amplitude modulation detection thresholds tested per subject. Correlation coefficients are also listed for comparison of the two psychoacoustic measures of temporal resolution for both UHL and NH subjects combined.