Research Article

Audiometric Testing With Pulsed, Steady, and Warble Tones in Listeners With Tinnitus and Hearing Loss

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Purpose: This study evaluated the American Speech-Language-Hearing Association's recommendation that audiometric testing for patients with tinnitus should use pulsed or warble tones. Using listeners with varied audiometric configurations and tinnitus statuses, we asked whether steady, pulsed, and warble tones yielded similar audiometric thresholds, and which tone type was preferred.

Method: Audiometric thresholds (octave frequencies from 0.25–16 kHz) were measured using steady, pulsed, and warble tones in 61 listeners, who were divided into 4 groups on the basis of hearing and tinnitus status. Participants rated the appeal and difficulty of each tone type on a 1–5 scale and selected a preferred type.

Results: For all groups, thresholds were lower for warble than for pulsed and steady tones, with the largest effects above 4 kHz. Appeal ratings did not differ across tone type, but the steady tone was rated as more difficult than the warble and pulsed tones. Participants generally preferred pulsed and warble tones.

Conclusions: Pulsed tones provide advantages over steady and warble tones for patients regardless of hearing or tinnitus status. Although listeners preferred pulsed and warble tones to steady tones, pulsed tones are not susceptible to the effects of off-frequency listening, a consideration when testing listeners with sloping audiograms.

Audiologists are tasked with obtaining a reliable, accurate audiogram in a relatively short period of time. However, many of the patients seen by audiologists also have tinnitus, which may complicate the ability of an audiologist or examiner to achieve this goal. A small body of evidence supports the thinking that tinnitus can interfere with the perception of tones presented during audiometric testing, potentially causing stress to the patient and leading to longer testing times (Dancer, Ventry, & Hill, 1976; Mineau & Schlauch, 1997). As a solution, the American Speech-Language-Hearing Association (ASHA) recommends using test stimuli that vary over time in either amplitude (such as pulsed tones) or frequency (such as warble tones), during audiometric testing for patients who report tinnitus (ASHA, 2005). The logic behind using such time-varied stimuli is that patients might have an easier time distinguishing a variable stimulus from their tinnitus. However, very few studies exist in the literature that support

the idea that pulsed and warble tones provide distinct advantages over steady tones, with essentially no studies focusing on the use of warble tones in audiometric testing for patients with tinnitus or hearing loss. Therefore, the goals of this study are twofold. The first goal is to evaluate whether steady, pulsed, and warble tones yield similar audiometric thresholds in listeners with and without tinnitus as well as with and without hearing loss. The second goal is to determine which tone type (steady, pulsed, or warble) is preferred by these same listeners.

Although ASHA has recommended for decades that audiologists should consider pulsed and warble tones over steady tones for testing patients with tinnitus, there is a paucity of literature on this subject. Most of the work on the topic addresses pulsed versus steady tones, and only two studies have directly addressed patients with tinnitus. Hochberg and Waltzman (1972) were perhaps the first to evaluate whether pulsed tones provide an advantage over steady tones at standard audiometric frequencies (0.25–8 kHz) for patients with tinnitus. They measured audiometric thresholds for pulsed and steady tones in two groups of listeners—one group had tinnitus and hearing loss and the other group had normal hearing. Hochberg and Waltzman found that both tone types yielded similar thresholds in both groups of listeners. Further, both groups demonstrated a

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strong preference for pulsed over steady tones. Mineau and Schlauch (1997) addressed this same question, but used a between-subjects design, in which a sample of patients with tinnitus was divided into two groups: One was tested with pulsed tones and another with steady tones. They also measured similar average thresholds for the pulsed and steady tones, but they found slightly higher false positive rates for steady versus pulsed tones and a greater number of trials needed to measure the audiogram when steady tones were used. Thus, despite the limited number of studies on this topic, pulsed tones do appear to provide an advantage over continuous tones for audiometric testing in patients with tinnitus, without influencing the accuracy of the audiogram.

Yet, the benefits of using pulsed tones over steady tones are likely not only applicable to patients with tinnitus. Results from a number of studies have suggested that pulsed tones are preferable for testing patients with normal hearing at standard audiometric frequencies, not just those with tinnitus. In groups of listeners with normal hearing, Hochberg and Waltzman (1972) measured a strong preference for pulsed tones, whereas Dancer et al. (1976) measured more false positives when testing with steady over pulsed tones. Burk and Wiley (2004) tested similar listeners and found no differences in false positive rates for pulsed versus steady tones, but they observed that 67% of participants preferred pulsed tones to steady tones for audiometric testing. Taking the results of these studies together, there is a clear benefit of using pulsed tones for testing listeners with normal hearing, either by reducing false positive rates, improving patient preference, or reducing the number of trials to complete an audiogram.

Despite the clear evidence in listeners with normal hearing and in listeners with hearing loss who also have tinnitus, no comprehensive study samples more broadly the variety of patients who are encountered in the clinic. In particular, two groups have been overlooked: listeners with normal audiometric thresholds who have tinnitus and listeners with hearing loss who do not have tinnitus. Therefore, it would be valuable to determine whether pulsed tones are advantageous to listeners in these two groups as well. Evidence obtained from a larger variety of listeners would provide a more robust foundation for the recommendations for clinical audiometry. Of particular interest is whether different patient groups might benefit from different types of test tones, or, in contrast, whether tinnitus and hearing loss have little impact on the best choice of test-tone type.

All of the aforementioned studies evaluated advantages of pulsed over steady tones, but to our knowledge, the benefit of using warble tones for patients with tinnitus has not been evaluated. The few studies evaluating the utility of warble tones in clinical evaluation of adults have focused exclusively on listeners with normal hearing. The earliest work focused on testing at standard audiometric frequencies. Dockum and Robinson (1975) tested a large cohort of listeners and established that warble tones yielded lower (better) thresholds (< 3 dB) than steady tones at four

of six standard audiometric frequencies, but they argued that the size of the threshold difference was not clinically significant. On the other hand, Barry and Resnick (1978) found that thresholds could be substantially lower for warble tones (> 5 dB) at standard audiometric frequencies. In their study, the size of the effect depended on both the modulation rate and the size of the frequency deviation. They posited that these threshold differences could be clinically significant (between 5–10 dB), and recommended that when audiologists find it necessary to test with warble tones, they should use a small frequency deviation and high modulation rate. Hamill and Haas (1986) further demonstrated lower audiometric thresholds for warble tones over steady tones in the extended high frequencies and consequently cautioned against using warble tones for high-frequency audiometry.

Taken as a whole, the cohort of studies evaluating the three different tone types in patients with tinnitus is a relatively sparse one. Very few of the previously mentioned studies compared results in patients both with and without tinnitus, and not all studies included patients with hearing loss. It is therefore unclear whether different groups of patients might require different tone types for audiogram measurement. Therefore, we believe that a more comprehensive assessment that evaluates patients with and without tinnitus as well as with and without hearing loss is needed. Further, the lack of evaluation of warble tones in these patients is surprising. Given ASHA's recommendation of the use of warble tones on patients with tinnitus, evaluating their validity in audiometric testing is profoundly warranted. To shed light on these concerns, we measured audiometric thresholds using three tone types (steady, pulsed, and warble), and evaluated preferences in four groups of people: those with hearing loss and tinnitus, those with hearing loss and no tinnitus, those with hearing thresholds within normal limits with tinnitus, and those with hearing thresholds within normal limits without tinnitus.

Method

Participants

Sixty-one total participants, ranging in age from 18 to 88 years of age, were divided into four groups, with each group defined by the participants' tinnitus and hearing status. Participants who did not experience tinnitus or who reported only "transient ear noise," lasting less than a few seconds, were placed in the no-tinnitus groups. Those with continuous tinnitus of any quality were placed in the tinnitus groups. Anyone not meeting either of these criteria (such as those with intermittent tinnitus), anyone needing medical referral, or anyone with an asymmetry between ears of more than 25 dB at two audiometric frequencies or an average asymmetry > 15 dB (at 0.5, 1, 2, and 4 kHz) were excluded from participation ($n = 9$ in total).

Participants with audiometric thresholds less than 26 dB HL at all standard audiometric frequencies (0.25–8 kHz) were considered to have hearing within normal

limits, subsequently referred to as “normal hearing” for simplicity. Participants were classified as having hearing loss if they met at least one of three criteria: low-frequency pure-tone average (PTA; 0.5, 1, and 2 kHz) of 30 dB HL or greater; high-frequency PTA (2, 4, and 8 kHz) of 30 dB HL or greater; or at least one hearing threshold exceeding 35 dB HL at any standard audiometric frequency. Both ears were required to meet the criteria to be included in the group of listeners with hearing loss. Of the 61 individuals included in this study, four did not meet the criteria of either normal hearing or hearing loss. These participants were used only in analyses that did not include group determinations. Ultimately there were 13 participants in the normal hearing without tinnitus (NH) group, 19 in the normal hearing with tinnitus (NHT) group, 14 in the hearing loss without tinnitus (HL) group, and 11 in the hearing loss with tinnitus (HLT) group.

Stimuli and Procedures

After taking a case history and performing otoscopy and ensuring clear ear canals, the examiner measured hearing thresholds in both ears via air conduction using a modification of standard audiometric procedures, as described by ASHA (2005). Nineteen participants were tested using a 6-dB down, 2-dB up procedure (nine in the NH group, nine in the NHT group, and one unassigned). All other participants were tested using a 10-dB down, 2-dB up procedure.¹

In three successive audiometric evaluations, hearing thresholds were measured using steady, pulsed, and warble tones. When testing with steady tones, pure tones were presented for 1–3 s. When testing with pulsed tones, three to five pure tones of 200-ms duration with 200-ms silent intervals were presented. When testing with warble tones, warble tones were frequency-modulated tones modulated at 5 Hz with a $\pm 5\%$ modulation depth and were presented for 1–3 s. Testing was completed at octave intervals between 0.25 and 8 kHz, 12.5 kHz, and 16 kHz for all listeners.²

Hearing thresholds were measured for the different tone types using a randomized-blocked design. The tone type was first selected at random, and then complete audiograms were performed for both ears with that tone type. After each audiogram was completed, listeners were presented with two questions in which they were asked to rate the appeal and difficulty of the test tone. Using a scale ranging from 1 to 5, listeners rated the appeal of the tones

(1 = *very unappealing*, 2 = *unappealing*, 3 = *neither appealing or unappealing*, 4 = *appealing*, or 5 = *very appealing*) and the difficulty of hearing the tones (1 = *very difficult*, 2 = *difficult*, 3 = *neither difficult or easy*, 4 = *easy*, or 5 = *very easy*). A short break was offered upon completion of the survey. This procedure was repeated until audiograms were measured and ratings collected for all three tone types. At the end of testing, participants indicated which tone type they preferred overall and their preference when tested using low and high frequencies.

Test stimuli were presented using a GSI Audiostar Pro (Grason-Stadler, Eden Prairie, MN) using HDA 200 circumaural headphones. All testing was conducted using these earphones as they are calibrated for all test frequencies, and testing was simplified by not having to switch transducers between standard- and high-frequency audiometry. Fifty-seven participants were tested in a sound-attenuating room, and four participants were tested in a quiet space in a local retirement community.

Results

Audiometric Results

One of the primary questions of this work was to establish whether steady, pulsed, and warble tones provide similar audiometric thresholds for a variety of listeners, including those with hearing loss. Therefore, rather than present average audiograms measured in these listeners, which would obscure the differences in threshold, we calculated the difference in threshold between pulsed and steady tones and between warble and steady tones for each listener. Those differences were then averaged together and are plotted in Figure 1 as a function of test frequency. Audiometric differences between pulsed and steady tones are shown in the top panels and differences between warble and steady tones in the bottom panels. Negative values indicate that thresholds were better (lower) for pulsed tones (top panels) or warble tones (bottom panels) when compared to steady tones. The left and right panels represent data from the left and right ears, respectively.

Figure 1 includes threshold differences only for frequencies at which thresholds were obtainable for all three tone types. In some cases, thresholds were not obtainable as the maximum audiometer output was 90 dB HL and 60 dB HL at 12.5 kHz and 16 kHz, respectively. In most instances, these data points were treated as “missing” data and were omitted from analysis. However, in a few cases, thresholds were obtainable for two of the three tone types in the same ear. In these cases ($n = 5$ for 12.5 kHz and $n = 1$ for 16 kHz), we set the no response value to equal the maximum audiometer output plus 2 dB (either 92 or 62 dB HL). Note that for the HL and HLT groups, thresholds at 12.5 kHz were obtained from at least 50% of the participants. At 16 kHz, of the 11 HLT participants, five had measurable thresholds in the left ear and six in the right ear. However, only one participant (left ear) and two participants (right ear) in the HL group had thresholds below the

¹Participants were tested by four different experimenters, with only one of them testing using the 6-dB down, 2-dB up procedure. We do not believe that this procedural difference has an effect on the interpretation of our data. First, threshold estimation was determined using ascending trials only, which had the same step size across experimenters. Second, the same procedures were used for steady, pulsed, and warble tones within a single participant.

²To obtain complete audiograms, some participants were tested at inter-octave frequencies and 10 kHz, following ASHA (2005) guidelines for audiometric testing. Due to the lack of having these thresholds in all participants, these data are not included in this analysis.

Figure 1. Difference thresholds between pulsed and steady tones are shown in the top panels and between warble and steady tones in the bottom panels. Negative values indicate that thresholds were poorer for steady tones than for either pulsed tones (top panels) or warble tones (bottom panels). Data from the different groups are shown using different symbols. NH = normal hearing without tinnitus; NHT = normal hearing with tinnitus; HL = hearing loss without tinnitus; HLT = hearing loss with tinnitus.

audiometer limits for all tone types. Thus, we have eliminated the 16-kHz data point from the HL group in Figure 1 to prevent the small sample size from biasing the trends.

Examination of the top panels of Figure 1 (pulsed thresholds minus steady thresholds) shows that, for the most part, pulsed tones and steady tones yield similar audiometric thresholds for standard audiometric frequencies. Threshold differences fall within ± 3 dB of each other, although there is a slight trend for thresholds to be better for the pulsed tones in the two groups with hearing loss (HL and HLT) for the left ear, evident in the negative threshold differences at the high frequencies. Because this trend is not present for the right ear, we suspect that the effect is more idiosyncratic than meaningful. The statistical analysis discussed below also does not support pulsed tones as yielding lower thresholds than steady tones.

On the other hand, the bottom panels of Figure 1 (warble thresholds minus steady thresholds) illustrate a general trend for warble tones to elicit better thresholds than steady tones for many of the frequencies, particularly those at and above 8 kHz. We can observe this as the relatively large negative threshold differences obtained in the extended high frequencies. The left ear demonstrates this result most

strongly, but the right ear also illustrates this result. At frequencies above 8 kHz, thresholds for warble tones are, on average, roughly 5 dB better than thresholds for the steady tones. It is interesting to note that the presence or absence of tinnitus (comparing the circles versus squares) had little effect on the tendency for warble tones to yield better thresholds than steady tones.

Due to the prevalent missing data at 16 kHz, we did not conduct an analysis of variance (ANOVA) on the complete data set. Rather, we conducted two repeated-measures ANOVAs: one using only standard audiometric frequencies and a second that included those frequencies and 12.5 kHz.³ The two ANOVAs revealed very similar results, and consequently, we report the results that included the 12.5 kHz data. Significant main effects of tone type,

³A repeated-measures ANOVA removes data obtained from any participant containing one or more missing data points. Given that all participants except one in the HL group had at least one missing data point, we chose to conduct the ANOVA by excluding the 16-kHz data in order to have a representation of the results obtained from the listeners with hearing loss.

$F(2, 84) = 9.93, p < .001$; group, $F(3, 42) = 182.3, p < .001$; ear, $F(1, 42) = 5.28, p = .027$; and frequency, $F(6, 252) = 45.0, p < .001$, were identified. Significant interactions were Ear $\times$ Group, $F(3, 42) = 5.43, p = .003$; Frequency $\times$ Group, $F(18, 252) = 17.8, p < .001$; and Tone Type $\times$ Frequency, $F(12, 504) = 2.67, p = .002$. Of these effects, only the ones involving tone type are related to the research questions. All other effects, except perhaps those in which the right ear had poorer thresholds than the left ear, particularly for listeners with hearing loss, were expected: Participants with hearing loss had higher thresholds than those with normal hearing and thresholds were poorer in the high frequencies for the HL groups (i.e., the losses were sloping).

Considering the significant effects that involved tone type, we see both an interaction between tone type and frequency and a main effect of tone type. It is of note that we saw no interaction between group and tone type, indicative that the effects related to tone type are similar across the four groups. Interpreting the interaction between tone type and frequency, post hoc t tests support the trend that, overall, warble tones elicit lower thresholds than either pulsed (1.9 dB; $p < .001$) or steady tones (1.6 dB; $p = .003$), but the threshold difference is largest in the extended high frequencies. For example, warble tones are, on average 3.9 dB and 5.5 dB lower than pulsed and steady tones at 12.5 kHz and 16 kHz, respectively.

Ratings

Recall that after each audiogram was measured with each tone type, participants completed a short survey in which they rated the appeal and difficulty of being tested for each tone type. Participants rated the appeal of the tones (1 = *very unappealing* to 5 = *very appealing*) and the difficulty of hearing the tones (1 = *very difficult* to 5 = *very easy*). Rating data obtained from the different groups for the different tone types are shown in Figure 2 for appeal and Figure 3 for difficulty. These figures illustrate cumulative rating functions, or the percentage of people selecting that rating or lower as a function of the rating. Plotting the data in this way allows an illustration of how the ratings vary (or do not vary) across the different tone types and across the groups.

For appeal, there were no differences in the median ratings across the different tone types or the four groups ($Mdn = 3$). The functions in Figure 2 demonstrate considerable overlap, suggesting no major differences in the appeal of the various tone types. Further, Figure 2 also illustrates that the majority of participants gave ratings of 3 or lower to all of the tone types. In all cases except one, more than 70% of participants gave the tones a rating between 1 and 3. The exception was the HL group, in which only 57% of participants gave the warble tone a rating of 3 or lower.

We also note that the participants with normal hearing tended to have a much greater percentage of unappealing ratings (1 or 2) than the participants with hearing loss.

Within the NH and NHT groups, an average of 27% of participants gave a rating of 1 or 2. In contrast, an average of 7% of participants gave such low ratings within the HL and HLT groups. We observe this result by looking closely at the tails of the functions plotted in Figure 2: These tails in the NH groups are higher on the y -axis than the tails of the HL groups. The median of 3 suggests that the participants had a fairly neutral perception of the appeal of each tone. Overall, we see little evidence that any of the tone types are more or less appealing than the others.

The Wilcoxon signed-ranks test supports these observations, as no statistical difference was found between the appeal ratings between steady and pulsed, steady and warble, and pulsed and warble tones ($p > .5$; $d < 0.12$ for all types). Statistics also bolster the interpretation that the participants with hearing loss assigned higher ratings than the participants with normal hearing. This trend was present across all of the tone types (Steady: $Z = 1.97, p = .056, d = 0.56$; Pulsed: $Z = 2.17, p = .03, d = 0.52$; Warble: $Z = 2.15, p = .03, d = 0.61$). Tinnitus status had no significant effect on the appeal ratings, though there was a slight tendency for the participants with tinnitus to find the warble tone less appealing than the participants without tinnitus ($Z = 1.86, p = .06, d = 0.48$).

Figure 3 illustrates the cumulative rating functions for the difficulty ratings. Of the 12 total difficulty ratings (three tone types $\times$ four groups), we note that three of the 12 had a median of 2. The NHT and HLT groups had a median ratings of 2 for the steady tone, whereas the NHT group also had a median rating of 2 for the pulsed tone. Although the medians are similar across the groups and tone types, the difficulty data do reveal slightly different patterns than observed for the appeal ratings. Figure 3 primarily illustrates a separation between some of the rating functions for the different tone types. Generally speaking, the cumulative distribution functions for the warble tones (shown by triangles) are to the right of the functions for the steady tones (shown by diamonds), indicating a greater proportion of lower (greater difficulty) ratings for the steady tones. The difference between steady and pulsed tone (plotted with circles) ratings is not as prominent, but still present, with only a slight separation between the functions. By evaluating the ratings associated with the greatest difficulty (1 and 2), on average, 58% of participants gave a difficulty rating of 1 or 2 to the steady tone, whereas only 45% and 38% gave those ratings to the pulsed and warble tones, respectively. As lower ratings are associated with greater difficulty, this result provides descriptive evidence that the steady tones are rated as more difficult than the other tone types. When assessing the data collapsed across groups, we observe that the steady tones were rated as being significantly more difficult than pulsed or warble tones (steady vs. pulsed: $Z = 2.33, p = .02, d = 0.41$; steady vs. warble: $Z = 3.02, p = .0025, d = 0.59$). Ratings for pulsed and warble tones were not significantly different from each other ($Z = 0.79, p = .43, d = 0.15$).

A second interesting finding is illustrated in Figure 3: Participants with tinnitus had a tendency to find all of the

Figure 2. Cumulative appeal rating functions are plotted for the different groups and different tone types. Data from the four different groups are shown in the four panels, plotted from left to right. Rating data from the different tone types are shown using different symbols, with diamonds, circles, and triangles denoting data from steady, pulsed, and warble tones, respectively. NH = normal hearing without tinnitus; HL = hearing loss without tinnitus; NHT = normal hearing with tinnitus; HLT = hearing loss with tinnitus.

tones more difficult than the participants without tinnitus. This effect was largest, and statistically significant, for the steady tone ($Z = 2.52$, $p = .01$, $d = 0.57$). Seventy-five percent of the participants with tinnitus gave a difficulty rating of 1 or 2 to the steady tone whereas only 41% of

the participants without tinnitus used those same ratings. Although these trends are present for the pulsed and warble tones, they are not as large and are not statistically significant ($Z = 0.93$, $p = .35$, $d = 0.24$ for pulsed tones, and $Z = 1.74$, $p = .08$, $d = 0.43$ for warble tones). Fifty-three

Figure 3. Cumulative difficulty rating functions are plotted for the different groups and different tone types. Data from the four different groups are shown in the four panels, plotted from left to right. Rating data from the different tone types are shown using different symbols, with diamonds, circles, and triangles denoting data from steady, pulsed, and warble tones, respectively. NH = normal hearing without tinnitus; HL = hearing loss without tinnitus; NHT = normal hearing with tinnitus; HLT = hearing loss with tinnitus.

percent of the participants with tinnitus gave a difficulty rating of 1 or 2 to the pulsed tone and 37% of the participants without tinnitus used those same ratings. Forty-three percent of the participants with tinnitus gave a difficulty rating of 1 or 2 to the warble tone, whereas only 32% of the participants without tinnitus did the same. Taken together, we observe that audiometric testing may be more difficult for participants with tinnitus overall, but we have clear evidence only for testing using the steady tone type.

There are also effects related to hearing loss. Participants with hearing loss and those with normal hearing gave similar ratings to the steady and warble tones (steady: $Z = 0.73$, $p = .43$, $d = 0.14$, and warble: $Z = 0.96$, $p = .34$, $d = 0.26$). However, the pulsed tone was rated as being less difficult by the participants with hearing loss than by participants with normal hearing ($Z = 2.5$, $p = .01$, $d = 0.68$).

The final measurement we made was to determine what tone type listeners preferred. Figure 4 plots the proportion of responses obtained for each group, as well as the entire set of 61 participants, as a function of tone type. For the full data set, participants tend to prefer the pulsed and warble tones, with only 25% of participants preferring the steady tone. Although there appear to be differences across the groups, the sample size of some of the groups is small, and we cannot easily draw strong inferences about the group differences. Furthermore, applying the Fisher's exact test indicates no significant difference in preference of participants on the basis of whether they

have tinnitus or not ($p = .89$; $N = 61$) or whether they have hearing loss or not ($p = .45$; $n = 57$).

Discussion

The purpose of this study was to determine (a) whether pulsed, warble, and steady tones yield similar audiometric thresholds regardless of whether listeners have hearing loss or tinnitus, and (b) whether these listeners prefer to be tested with a time-varying stimulus during audiometric assessment. First, our findings indicate that warble tones yield lower thresholds than pulsed or steady, most prominently in the high frequencies. A participant's hearing or tinnitus status does not affect this result. Further, pulsed and steady tones yield similar thresholds at all frequencies, including the extended high frequencies. Second, the rating data demonstrated a number of strong advantages to testing with pulsed or warble tones. These two findings are discussed in turn.

The finding that warble tones elicit lower audiometric thresholds is not new, but no study has presented data on listeners with hearing loss or tinnitus. Therefore, our results extend the findings of Hamill and Haas (1986), who observed better thresholds for warble tones in listeners with normal hearing to include listeners with hearing loss and those with tinnitus. Consistent with previous work in listeners with normal hearing by Dockum and Robinson (1975) and Barry and Resnick (1978), we also observed slightly lower thresholds for warble tones compared to both pulsed and steady tones at standard audiometric frequencies for

Figure 4. Proportion of participants preferring each tone type by group and for the full set of 61 participants. The different gray scale bars illustrate data from the different groups. The lightest bars reflect data collapsed across all 61 participants. Groups are denoted by hearing status. NH = normal hearing without tinnitus; NHT = normal hearing with tinnitus; HL = hearing loss without tinnitus; HLT = hearing loss with tinnitus.

listeners with tinnitus and hearing loss. We also observed this effect to be very small, averaging less than 3 dB. The authors of these previous studies have argued that the relatively small difference in threshold is not clinically significant, and those authors support the ASHA recommendation that using warble tones for standard audiometry is appropriate. Although our data support this claim, we note that the threshold difference between the different tone types can be very large, ranging between -14 and $+14$ dB.

Using warble tones for standard audiometry also poses an additional concern related to the role of off-frequency listening in tone detection. Hamill and Haas (1986) posited that the lower thresholds for warble tones is caused by off-frequency listening, in which the frequency spread of a warble tone allows regions of hearing with better sensitivity to detect the tone. Hamill and Haas tested this in a single person, but our data set, which has many participants with a variety of hearing levels, can provide an additional, post hoc test of this hypothesis. We can assess this hypothesis indirectly by evaluating the threshold difference between warble tones and the other tone types in listeners with and without sloping audiograms. The logic is as follows: Listeners with flat audiograms should not need to rely on off-frequency listening to the same degree as listeners with sloping audiograms, as a low-frequency region in a sloping audiogram would provide better hearing than the region intended to be active by the test tone. If off-frequency listening contributes to the better thresholds for warble tones, then we should observe a correlation between the slope of hearing loss and the improvement in threshold given by warble tones. Those with greater sloping audiograms should rely more heavily on off-frequency listening, thereby yielding better warble tone thresholds than for the other tone types.

To test the contribution of off-frequency listening, we calculated the slope between the 4, 8, and 12.5 kHz thresholds for steady tones (left and right ears separately) and correlated these with the difference in threshold between warble tones and steady tones at 12.5 kHz. Figure 5 illustrates the relationship between audiometric slope and the threshold difference and shows that audiograms with large slopes tend to be associated with a large negative threshold difference between warble and steady tones. Therefore, steeper audiograms may be linked to better warble tone thresholds, although, as Figure 5 illustrates, there is substantial variability in this relationship. We found a negative correlation of $-.45$, significant at the $p < .001$ level. This correlation increased slightly to $-.47$ when the single outlier (the data point with a threshold difference between the warble and steady tone of -28 dB) was removed. This trend was also evident at 8 kHz using the slope calculated from 2, 4, and 8 kHz ($r = -.29$; $p = .002$). Therefore, it appears that off-frequency listening can contribute to a lower warble tone threshold, which could be more than 10 dB better than the threshold obtained for a steady tone.

Taken together, our data have replicated findings that warble tones elicit lower thresholds than either pulsed

or steady tones in a large group of listeners. For most frequencies, the threshold differences are very small and average less than 3 dB. These differences would be acceptable within a clinical situation where a > 5 dB change in threshold is necessary to be considered clinically significant. However, audiologists should carefully consider the implications of using warble tones during audiometric testing for listeners with sloping audiograms and for testing at frequencies of 8 kHz and above. In both cases, off-frequency listening might yield thresholds that overrepresent hearing abilities. The resulting audiogram may therefore not reflect the true hearing abilities of these patients. On the basis of the threshold data, we advise caution when using warble tones for audiometric testing in the higher frequency regions, in support of the recommendations by Hamill and Haas (1986).

With regards to the rating data, we have clear evidence against using steady tones for audiometric testing. Although a larger sample size would lead to more robust recommendations, the rating data presented here already allow some reasonably strong conclusions against testing with steady tones. The difficulty data support the broadest claims against testing using steady tones, and combining the interpretations from the difficulty with those of the appeal data provides support for testing with pulsed tones rather than warble tones.

First, when analyzing the difficulty data across all groups, the participants rated testing with steady tones as significantly more difficult than testing with pulsed or warble tones. Second, when separating the groups on the basis of tinnitus status, participants with tinnitus gave lower difficulty ratings (greater difficulty) to the steady tones than the participants without tinnitus. Last, only 25% of the participants preferred testing with steady tones, suggesting that most patients would prefer a variable tone type. These preferences were present across the entire group of participants and appeared to be independent of tinnitus or hearing status. These results are consistent with those of previous studies, which found that most listeners tend to prefer pulsed to steady tones (Burk & Wiley, 2004; Hochberg & Waltzman, 1972). Our results extend their findings to include a preference of warble tones as well.

ASHA's recommendation to use time-varied stimuli for patients with tinnitus is rooted in a logical argument that a time-varied stimulus would reduce confusion between test tones and tinnitus. Mineau and Schlauch's (1997) study supports this recommendation, as they found that the number of trials to obtain an audiogram was higher for continuous tones compared to steady tones. Their study, however, only included patients with tinnitus, and therefore they could not assess whether this recommendation should only apply to patients with tinnitus. Our rating data, interestingly, demonstrate advantages of the pulsed and warble tones for all patients, not just those with tinnitus. We observed that pulsed and warble tones were perceived as being less difficult to detect than steady tones across all of our groups and that 75% of participants preferred the time-varied tones over the steady tones. We support ASHA's

Figure 5. Illustration of the relationship between audiogram slope (obtained from 4–12.5 kHz) and the threshold difference between warble and steady tones for all listeners and both left and right ears. Individual data points are plotted along with the regression line.

recommendation that variable tones are better for testing patients with tinnitus, but our data also indicate that variable tones lower the difficulty of the detection task for patients without tinnitus, regardless of hearing or tinnitus status. Burk and Wiley's (2004) data support this claim as well. They measured lower false positive rates and higher preferences in listeners with normal hearing (without tinnitus) for pulsed tones over steady. On the basis of the difficulty and preference data and previous literature, we argue that audiologists choose a time-varied tone for testing of all patients, not just those with tinnitus.

Although generally the participants appeared to benefit from the time-varied tones, two pieces of evidence in the rating data suggest that pulsed tones are preferable over warble tones for audiometric testing. First, the appeal rating data revealed that participants with tinnitus found the warble tones to be less appealing than the participants without tinnitus did. It is unclear why this result might have occurred. However, because this observation was not present for the other tone types, perhaps the frequency sweep of the warble tone interacts with a participant's tinnitus in a negative and displeasing way. Second, the participants with hearing loss gave higher (less difficulty) ratings to the pulsed tone than the participants with normal hearing did. Again, it is not clear why hearing loss might interact with the perception of difficulty, but perhaps the pulsed tone reduces the cognitive load expended in audiometry more for those with hearing loss. Regardless, however, using tone types that are perceived as easier to hear is likely to reduce test time, patient fatigue, and stress. As most

patients in audiology clinics will have some type of hearing loss, using pulsed tones might reduce the task difficulty for the majority of patients.

Conclusions

Taking the audiometric data in conjunction with the rating data, we suggest that pulsed tones provide significant advantages over both steady and warble tones for all patients regardless of hearing or tinnitus status. Pulsed tones reduced the perceived difficulty of the task, were preferred by many listeners, and yielded similar audiometric thresholds at all frequencies to steady tones. Although warble tones had a similar effect of reducing perceived difficulty and were also preferred by many participants, these tones can be subject to off-frequency listening, thereby yielding anomalous audiometric thresholds. Particularly notable, however, is that the patients with tinnitus did not find the warble tone as very appealing. Warble tones may be appropriate in some situations, but audiologists should carefully consider whether the benefits of using warble tones outweigh the drawbacks.

Because we observed that the patients with tinnitus perceived the audiometric procedure to be relatively difficult overall, particularly in reference to testing with steady tones, the steady tone might be associated with greater listening effort for patients with tinnitus compared to those without. Follow-up measurements of listening effort could allow us to gather insight into this hypothesis. Consideration of other test stimuli or procedures that could reduce

task difficulty might also be warranted in these populations in an attempt to relieve the hypothesized additional listening effort.

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