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Lateralization of Pitch Processing

Daniel Rynerson

Abstract

In the perception of language, studies have shown that the right ear and left hemisphere (RELH) pair processes linguistic syllables more readily than the left ear right hemisphere (LERH) during simultaneous presentation. This phenomenon is known as the Right Ear Advantage (REA). This is believed to occur due to the proximity of language processing areas in the left hemisphere to the left hemisphere reception of cortical auditory signals predominantly from the right ear. An analogous Left Ear Advantage (LEA) has also been reported for pitch processing, presumably with its center of processing in the right hemisphere. The current study replicates and extends a previous finding of LEA for pitch processing using an experimental protocol involving a dichotic, single ear, pitch processing task where judgements in pitch are made using an AXB discrimination task. Results demonstrate that across most tone bases and tone difference conditions, the effect of ear of presentation is not significant. The LEA was found to be limited in that it achieves a significant difference between the ear of presentation only within the small tone difference condition when collapsed across all trials and frequency ranges. Moreover, some findings in this condition were near chance responding, demonstrating the need for more nuanced manipulations in testing parameters for human hearing. The 1,000Hz condition demonstrates the largest interaction effect, displaying significance in the small tone difference condition, thus informing where the phenomenon of LEA may be most prevalent.

MONTCLAIR STATE UNIVERSITY

Lateralization of Pitch Processing

by

Daniel Rynerson

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Lateralization of Pitch Processing

Lateralization and localization of function were discovered early in perceptual processing with each sensory modality occupying a specific part of the brain (Jackson, 1874). Lateralization is noted when the processing of information is done predominantly site specific, being performed on one side or hemisphere of the brain over the other. Somatic information which includes bodily movement, sensation, and aspects of perception decussate or cross hemispheres to be received in the contralateral brain hemisphere. For example, information from the right and left visual fields extend to opposing hemispheres for processing and is then further localized for color, orientation, and other factors. Likewise, in auditory processing, the majority of perceptual information from one ear extends to the contralateral hemisphere's auditory cortex (Moore, 1997). Furthermore, aspects of listening to spoken language engage multiple parts of the brain for interpreting semantic meaning, pitch inflection, and grammatical subject-object representations that all give different cues to listener (Zatorre, Evans, Meyer & Gjedde, 1992; Cascino, 2002).

The difference of auditory processing between brain hemispheres arises when these incoming signals are interpreted and coded for by localized brain regions and often, in terms of language or pitch, become lateralized to one main hemisphere, influencing how speech perception occurs. The general pathway for auditory information moves from both ears to converge in the Superior Olivary Complex of the hindbrain, then passed upwards for processing in Inferior Colliculus of the midbrain and ultimately routed to the primary auditory cortices via the medial genicular nucleus of the thalamus (Moore, 1997). Depending on the task orientation, secondary auditory regions are activated for processing of pitch or linguistic information such as the commonly known Broca and Wernicke areas in the left hemisphere in understanding language. This lateralization has been experimentally tested using the discrimination of speech syllables and shows a preference for the right ear stimulus to be identified over the left when different syllables are presented to both ears simultaneously (Berlin, Lowe-Bell, Cullen, Thompson, & Loovis, 1973; Ip & Hoosain, 1993; D'Anselmo, Marzoli, & Brancucci, 2016).

Pitch inflection in speech also adds to the semantic information such that the interpretation of questions or statements are inferred by the acoustic parameters giving additional information to the listener (Juslin, 2003; Wong, 2002). Various experimental designs test the lateralization of function or hemispheric differences in the processing of pitch similarly, by using listening tasks where participants make judgements or tone discriminations in various Hertz ranges to infer the degree of processing strengths or unilateral advantages in processing (Pell, Jaywant, Monetta & Kotz, 2011; Sininger & Bhatara 2012; Zatorre, Evans, Meyer & Gjedde, 1992). If pitch processing is lateralized in the brain, processing differences between brain hemispheres and therefore between the ears may reflect differences in these judgements through the overall accuracy of the pitch discriminations made. The current study assesses the supposed right-hemisphere specialization for non-speech tone perception by replicating and extending a listening task in which both ears are separately presented with a three tone sequence to measure differences in accuracy between the brain hemispheres within different pitch frequency ranges or tone bases and the proximal difference conditions.

A Psycholinguistic Perspective

One of the goals in linguistics is creating a structural model of how language is organized into concepts, where rules such as syntax and generative grammar construct distinctive interacting parts that guide the production and interpretation of language. But with continually bettering technologies such as fMRI, the hardware of the brain may hold its own distinctions and integrated pieces that formulate structures to represent language. Comparisons between these models can inform a deeper understanding of how linguistic structures and the understanding of speech occurs within neurological networks of the brain rather than within our own contextual delineation of the use of language.

This merger of linguistic understanding with new neurological models implies the need to revise concepts of how the brain represents such constructed linguistic distinctions compared to the standard differentiation by language users into parts of speech, grammar, and subject-object representations. Testing of individuals with brain lesions and other localized brain damage can give insight into how specific regions of the brain correlate to alterations in performance in prosody, phrasing, and understanding; thus informing aspect of language creation and interpretation (Alexander & Annett, 1996). However, these rules are concepts formed within the context of rule-based language interpretations (Bates & Goodman, 1997) and hold "the assumption that our linguistic models have an orderly presence in [the] functional structure or organizational principles in the brain" (p. 204, Van Lancker Sidtis, 2006). The improvement of understanding comes from determining whether these two methods are in parallel in how they delineate and represent language. Similar to the previous example in vision, being broken down to components of color and orientation, so too are the aspects of speech broken into their component parts for interpretation and representation within the biological brain. For the purpose of experimentation, the use of behavioral tasks can be employed to pull apart different aspects of language such that phenome identification, representing grammatical structures, and even pitch can be isolated and tested to indicate if a hemispheric superiority exists within different aspect of language processing.

Left Hemisphere Processing & Right Ear Advantage for Speech Perception

The left hemisphere is known for processing linguistic information and this lateralization has been experimentally verified using discrimination tasks of speech syllables. The paradigm of dichotic listening is used to test laterality and selective attention, where simultaneous presentation of stimuli occurs in both ears (Hugdahl, 2015). In one of the early studies using this design, Studdert-Kennedy and Shankweiler (1970) demonstrated a significant advantage in the right ear for identifying consonant differences when two ‘consonant-vowel-consonant’ mono-syllables “pet”, “bap", "doop", "pawg", are presented in both ears simultaneously. Participants are asked to identify both items presented to either ear. Overall, a 12% advantage is found in the correct identification from the right ear over the left ear when consonant differences are presented between ears. This revealed a phonetic processing distinction occurring between the presented sound stimuli and the ability of the auditory cortex to register and process the co-occurring information. They conclude “while the general auditory system common to both hemispheres is equipped to extract the auditory parameters of a speech signal, the dominant [left] hemisphere may be specialized for the extraction of linguistic features” (p.593, Studdert-Kennedy & Shankweiler, 1970).

This Right Ear - Left Hemisphere (RELH) dominance of language processing has come to be known as the Right Ear Advantage (REA) in common Psychophysics literature. The theory holds that the proximity of the language processing centers in the left hemisphere are nearer to the left auditory cortex receiving right ear stimulus and leads to a more expedient processing by these left lateralized linguistic brain areas. Therefore, leading to the perceptual prominence of the Right Ear – Left Hemisphere (RELH) pair over the Left Ear - Right Hemisphere (LERH) for processing of spoken word syllables during simultaneous presentation of speech syllables.

A more recent study by D’Anselmo, Marzoli and Brancucci (2016) used a dichotic experimental design that presents two different but similar sounding syllables or phonemes (da, la, ba, ma, etc.) to both ears simultaneously. In the task, the listener is asked to identify both syllables, therefore identifying the stimulus of both ears. On average, participants consistently and naturally identify the syllables played in the right ear more accurately than the left ear (19%) in this part of the task. Designs such as these provide behavioral evidence for the theory of language lateralization through observed significant differences in the ear of reporting as a function of the phonological features in presented sounds.

In another experiment, the REA is also confirmed to exist for identifying verbally spoken numerals with an approximate 7% advantage found in the right ear (Kimura, 1961) referring to a “prepotency” between the language centers and the incoming right ear signals. Ip and Hoosain (1993) looking at a cross language application, used a similar dichotic listening design with bi-lingual Chinese Americans. Results show that the right ear – left hemisphere (RELH) advantage for language discriminations persisted in both their native Chinese language and secondarily learned English language. Mandarin, as a tonal language, uses pitch variations to imply changes in lexical meaning known as lexical stress and is, therefore, still left hemisphere dominant in processing different word-phrases. In this way, a quantified linguistic preference is found in the difference in performance of the ears implying the neuroanatomical placement for phonemic processing on the left side of the brain. This also gives credence to the representation of language with a more universal representation in the left hemisphere specialized for linguistic processing.

Berlin, Lowe-Bell, Cullen, Thompson, and Loovis (1973) also found a 14% advantage to the right ear stimulus, specifically noting that this advantage persists even when right ear presentation is delayed by 15 milliseconds however, reported significance drops off at a 30 milliseconds delay. Ozgoron (2012) found a similar a lag-effect or time delay within the simultaneous presentation of stimuli, up to 35ms, diminishing the prominence of REA in the perceptive process. This experimentally demonstrates an expediency in processing in that reporting of linguistic or phonetic information (speech stimuli) persists in the RELH over the opposite LERH stimuli even with a time delay that could potentially diminish the effect of this advantage. Therefore, the difference in processing time between hemispheres may approximate within the 15 and 35 millisecond range due to the decussated wiring of the brain. Volume or intensity of the syllables presented is also known to alter the response of participants against the prominence of REA (Tallus, Hugdahl, Alho, Medvedev & Hamalainen, 2007), as it can increase the prominence of either incoming signal. The current study maintains a unilateral presentation (non-competing auditory signals) with equal volume intensity across tones in each trial to negate any distortion to the temporal or perceptive process during the experiment.

Semantic or phonetic information processed within the left hemisphere leads to a processing superiority of the right ear stimuli over the left ear stimuli in the presentation of verbal stimuli. This effect is believed, in part, to be connected to the decussation and majority of projecting neural fibers from the ear to contralateral hemisphere, 60% contralateral and 40% ipsilateral (Moerel, De Martino, & Formisano, 2014). The left ear neural fibers project their majority to right hemisphere cortex so that linguistic information originating in the left ear needs to cross hemispheres to be processed within left hemisphere speech areas. This biological implication may be causal to the perceptual predominance in audition demonstrated during the simultaneous presentation of speech syllables to both ears. The contralateral distinction is also seen in patients with split brain, where the corpus callosum is severed. During assessment of these patients, reports show that verbal responses governed by the left hemisphere go un-reported when stimuli are presented to the opposing right hemisphere as it has lost its direct connection the left hemisphere speech areas (O'Shea, 2003). However, when asked to report by pointing with the left hand, a response governed by the right hemisphere, that area then displays the correct behavior, pointing with left hand, in ascertaining the correct response.

Criticisms of these tasks report a potential problem as the responses are a freely reported measure by the participant themselves leaving it susceptible to attentional redirection (Bryden, 1969; Sætrevik & Hugdahl, 2007). In this manner, the nature of the stimulus can be somewhat disregarded if the participants' attention can be deliberately placed on one ear or the other in naturalistic reporting. In one such study, a condition is given for Forced Left Ear listening in the speech processing task with the same simultaneous presentation paradigm (Hugdahl, Carlsson, & Eichele, 2001). When asked to focus solely on the left ear, participants were able to overcome the REA and report the left ear stimulus over the right with attentional modulation, demonstrating that the task is highly susceptible to a participant's attentional redirection. The current study's experimental design specifically separates trials for each ear, bypassing issues with attention or competition between ears seen in the dichotic listening tasks. Therefore, the participant's attention is not divided to either the left or right ear but rather, fixed, depending solely on the trial condition presenting to one ear for the duration of a block of trial tasks.

Right Hemisphere Processing and Left Ear Advantage for Tones

Similar to the contralateral phonetic processing, it is theorized that pitch inflections or affective tonal qualities that are not linguistically relevant are conversely processed by the right hemisphere. Pitch inflection in speech tends to add to the semantic information to infer emotion, attitude, and intent of the speaker. Alterations of pitch can be very subtle but can lead to strong changes in meaning that occur in questions or through emphasis in statements where the acoustic parameters give additional information to the listener (van Lancker Sidtis, 2006; Wong, 2002). Although speech is largely interpreted by the left hemisphere, these particular non-linguistic aspects of speech are thought to be attributable to the right hemisphere where it contributes to the understanding of general discourse. Juslin (2003) proposes that there are underlying acoustic patterns in tempo, intensity, and timbre that arise in speech as well as music which invoke emotional interpretation and implicit judgements about the tone of the speaker.

Both prosodic and semantic cues give information to the listener in speech and represent to some degree the difference in hemispheric processing between pitch and linguistic distinctions within verbal communication. The appraisal of emotion within language can be determined through multiple channels. Each aspect, although immediately present in speech stimuli are encoded differently and give different cues in interpretation (Pell, Jaywant, Monetta & Kotz, 2011). Prosody implies alterations of pitch and rhythm in speech, while semantics refers to the linguistic implication of the words themselves. In making these judgements on emotion from an auditory speech source, it is shown that the brain's response has two different ERP sequences depending on whether attention is focused on violations in prosodic expectations compared to when they match their semantic meaning (Kotz & Paulman, 2007). This implies differing neural pathways or networks involved in assessing linguistic interpretations and prosodic pitch changes or emotional tone. It is shown that these semantic cues or linguistic meanings of the statement take precedence in judging the speaker's emotion (happy, sad, or neutral) when given the mismatch between the two, emotional prosodic versus semantic processing. A right-lateralized frontal cortex positivity (P2) is seen during prosodic mismatches implying that this part of the brain may be detecting the mismatches in auditory pitch where their emotion-related content does not match the semantics. Therefore, it is theorized this part of the brain to be dominant in deciphering pitch, identifying when these violations of prosody occur, and therefore detecting these discrepancies.

Investigations of tonal languages, such as Mandarin Chinese found similar activations of the right hemisphere in discerning overall pitch level (high versus low frequencies) but found left hemisphere activation in pitch contour. Contour in a tonal language can denote semantic changes therefore registering in a linguistic lexicon inferring weight in semantic meaning, as the direction of pitch change over time (Wang, Wang, & Chen, 2013). However, static pitch discriminations are shown to be determined faster than those of pitch contour in this experiment as their semantic alteration would modify the degree of hemispheric lateralization necessary for interpretation. This adds to the understanding of auditory processing and the temporal orientation of pitch as a rather dynamic synthesis of both right and left hemisphere activation occurring in the interpretation of tonal languages.

Clarifying these distinctions further, Zatorre et al. (1992) used positron emission tomography to assess auditory discriminations across both hemispheres. Activations of both primary auditory cortices was found with listening to noise bursts, but specifically with speech syllables there was bilateral activation of secondary auditory cortices. When participants were asked to make distinctions in identifying parameters of speech, activation was found to be left lateralized, namely in Broca’s area. However, when distinctions were made for differences in pitch, once again a right pre-frontal cortex activation was found, inferring this hemisphere’s dominance in pitch processing.

Sininger and Bhatara (2012) assessed difference between ears in thresholds for tones. Their design used multiple frequency ranges (500 Hz, 1000 Hz, 4000 Hz) and a three-alternative forced choice paradigm where three tones are presented, and participants identify which of the three tones differs from the other two. Each ear is given this task individually to test for laterality, operationally defined as the performance difference between the ears. For pitch discrimination threshold estimate, the experiment begins with a large 50 Hz difference which after two correct responses is reduced by a factor of 1.5, incorrect answers yield an increase of factor by 1.1. The study concluded left ear performance to be superior in all ranges but with significance of ear difference (laterality) established within the 1,000 Hz condition only. The 500 Hz condition displayed similar thresholds for tone discrimination of around 5 Hz closely equivalent in both ear conditions. The 4,000 Hz condition displayed a threshold of approximately 30 Hz, again with close to equivalent discrimination between ears. The 1,000 Hz condition yielded approximately 6 Hz in the left ear and a lesser discrimination of approximately 8 Hz in the right ear; a 2 Hz difference between the ear of presentation. Different stimulus durations (200ms, 500ms, 1000ms) were also tested, however, they found no significant effect of duration on the ability to discern pitch changes. It is discussed that alteration of the LEA may occur in binaural stimulation, thus white noise is added in the opposing ear to increase "contralateral spectral processing capacity" (p. 146; Sininger & Bhatara, 2012).

Since manipulations were made with 500 Hz, 1000 Hz, and 4000 Hz frequency bases, the current study will test below and between these frequencies assessed to include those closer to the vocal fundamental frequency range at 100 Hz and 200 Hz (relevant for voice pitch contour) as well as testing frequencies within the higher range of 1000 Hz (for replication) and 2000 Hz that overlap with information for consonant differences (Vickers, et al., 2009). Whether these higher frequency distinctions show a left or right advantage, can inform the distinction in processing between hemispheres similar to how tonal language manipulations are left hemisphere registered in making semantic pitch distinctions (Ip & Hoosain, 1993).

These differences in auditory processing between hemispheres of the cerebral cortex may lead to the unilateral perceptual advantage in pitch processing. This phenomenon is much less studied than the known REA for linguistic discriminations as more recent literature is beginning to discuss a Left Ear Advantage (LEA) for pitch processing (Pell, Jaywant, Monetta & Kotz, 2011; Sininger & Bhatara 2012; Zatorre, Evans, Meyer & Gjedde, 1992). Thus, in the presentation of sound to the opposing ears and therefore the opposing hemispheres, it is possible to test aspects of auditory processing such as non-linguistically related pitch discrimination. How accuracy of these processes change due to these parameters can help inform interpretations regarding to the lateralization of pitch processing to the right hemisphere. The current study will test this idea using a targeted listening task such that the left ear presentation should show processing superiority in discriminating differences in pitch.

The Current Study

The current study design assesses whether nonlinguistic pitch processing will demonstrate a LEA due to lateralization of processing in the right hemisphere. If no difference occurs between ears, it may be presumed as bilaterally processed in the brain. Therefore, a pitch discrimination task will be given to each ear individually (non-competitive dichotic listening) in order to avoid previously discussed issues of attention. When auditory processing crosses hemispheres similar to tactile or other sensory information, the LE-RH should process the discrimination of pitch information more accurately as it connects this sensory information more immediately to those right hemisphere pitch processing centers. Conversely, the RE-LH pair will have its sensory cortical information received on the contralateral side (left hemisphere) of where pitch processing occurs (right hemisphere), potentially reducing accuracy. Reaction times were a potential method of investigation however appropriate equipment for precise measurement was not available for use in this study. Although these data points are usually not normally distributed, a truncated version of the data was used to allow accurate analyses of participant responses within a reasonable adherence to appropriate responding (Baayen & Milin, 2010).

The proposed study will assess the LERH specialization for non-speech tone perception by replicating and extending a listening task in which both ears are separately presented with three tone sequences. This experiment is devised as a single ear pitch processing task that will test the validity or presence of an LEA for pitch processing. The participants will be asked to make simple judgements regarding these differences of pitch in each ear dependent on the task condition. The design used to test for frequencies is an AXB pitch discrimination task, where a binary response pattern is established to determine whether the LEA is discoverable and verifiable at select frequency ranges. It was hypothesized that the LERH will show a performance advantage in tone discrimination with potential interactions in base tone level (high versus low) or base tone (100 Hz, 200 Hz, 1000 Hz, 2000 Hz), and the magnitude of difference between tones (large, medium, small).

Methods

Participants

A total of 42 participants, (34 female, 9 Male, average age 19.8) from the Montclair State University undergraduate student community participated in the study for course credit. Prior to being included in the study, participants self-reported having normal hearing and speech perception. There were 40 right handed and 2 left handed individuals. Due to imbalanced representation in handedness, this is unlikely to influence pitch processing across participants.

Materials

The basic design of the AXB pitch discrimination task involves a base tone frequency as the middle X tone which is compared against differences from the base tone, A and B that are presented proximal to the middle tone to be discerned by the participant in the listening task. Differences from the base tones (100 Hz, 200 Hz, 1,000 Hz, & 2,000 Hz) were determined by estimating near-threshold tones customized for each base tone frequency yielding a large, medium, and small difference conditions. For the 100 Hz base tone, comparison tones differed by 1 Hz, 2 Hz, and 3 Hz (rendering the below baseline frequencies as 97 Hz, 98 Hz, 99 Hz and the above baseline frequencies as 101 Hz, 102 Hz, 103 Hz). A similar procedure for the 200 Hz base tone yielded comparison tones at above and below 2 Hz, 4 Hz, and 6 Hz. The higher frequency base tones, 1000 Hz, and 2000 Hz condition, follow with plus and minus 5 Hz, 10 Hz, and 15 Hz differences. Appendix A displays the tone values used to compose the AXB tests.

All tones were generated using Praat software (www.praat.org; Boersma, 2001). Depending on pitch, the perceived loudness to the listener will change. Higher frequencies are naturally perceived as louder to the listener than lower frequencies of the same decibel level. In order to account for this phenomenon, known as the equal loudness contour (Fletcher & Munson, 1933), lower frequency base tones and their comparison tones were presented at slightly higher intensity levels than the higher frequency base tones. With this rationale, the low 100 Hz and 200 Hz frequencies were presented at 70 dB (exactly synthesized at .1 Pascals or 70.97 dB) during the listening task and the higher 1,000 Hz and 2,000 Hz frequencies presented at approximately 60 dB (exactly synthesized at .03 Pascals or 60.51 dB) to compensate for the differences of sensitivity in human hearing to higher frequencies. The table referring to the equal loudness contour conversion is in Appendix B.

Procedure

The experiment involves identifying the different tone within a three tone AXB series. For each trial, the base tone frequency (either 100 Hz, 200 Hz, 1000 Hz, or 2000 Hz) was presented in the middle of the three tone series (X) and the comparison tones were consistently randomized in order to place one differing tone either as the first or last tone of the sequence (A or B) with the other simply matching the base frequency. Each tone in the AXB triad was 500 ms long and had an inter-stimulus interval of 500 ms, mirroring the middle condition seen in Sininger & Bhatara's (2012) experiment for perceptual salience. Each AXB trial prompted a keyboard response from the participant to identify the different pitch within the series (first or last). Participants were instructed to press the "1" key if the first tone was different and the "0" key on the opposing side if the last tone was different. After each response to an AXB trial, the next trial was presented automatically with a 1000ms delay.

Each individual trial, which includes the base frequency and its comparison tones, are then paired with a white noise track in the opposing ear at low threshold, relatively half the decibel rating of the audible tones. Therefore, the individual sound file is presented to either the right or left ear with the opposing channel containing the white noise to ensure activation of both auditory pathways yet allowing for targeted tone discrimination solely in the ear of tone presentation (Brown, 1999; Sininger & Bhatara, 2012.). Each sound file is then arranged in this manner, presenting each tone with its white noise counterpart in opposing ear using the audio program Cubase (Steinberg, 2014).

Presentation of AXB trials and data collection took place in sound-attenuated booths via MacIntosh computers running SuperLab 5.0 (Haxby, Parasuraman, Lalonde, & Abboud, 2014). The experiment comprised 4 blocks, counterbalanced in presentation by the tone type (high or low tone discriminations) and ear (right or left). A total of 196 trials allows for 48 distinctions within each ear by tone type block amounting to 15 to 20 minutes for the full experiment. Data was automatically recorded and formatted by the SuperLab program for AXB accuracy. According to the experimental hypothesis, the LERH pair should score significantly higher on the number of correct pitch discriminations displaying an LEA indicative of pitch processing on the ipsilateral right hemisphere.

Data Analysis

Participant responses were filtered to eliminate trials in which participants did not follow instructions by pressing the space bar rather than the 0 or 1 keys. This filter lowered the overall trials minimally from 8,063 to 7,969 (1.2% reduction). In addition, trials were filtered by response time to eliminate those responses that were faster than typical choice response times, as well those taking too long to respond with the criteria set between 100 and 5000 milliseconds. This procedure further reduced the amount of trials in analysis by 832 (10% reduction) from 7,969 to 7,137 trials.

Data analysis was performed using R statistical platform (RStudio, 2015). In the data aggregation, descriptive statistics estimated the proportion of correct responses for each ear averaged across participants, compared to chance responding in the binary AXB task, which is 0.50. A two-way repeated measures analyses of variance assessed the influence of ear of presentation (LERH versus RELH) and the degree of difference from the tone base (large, medium, or small). This procedure was repeated for each tone type (high or low) and then within each tone base (100 Hz, 200 Hz, 1000 Hz, 2000 Hz).

Results

To assess potential for an overall LERH advantage, the performance for left ear and right ear collapsing across all frequency (base tone) conditions and tone differences (large, medium, or small difference from base tone) was 0.559 for LERH (*SD*= 0.083) and 0.550 for RELH (*SD*= 0.082). This pattern for ear difference was not significant in the analysis of variance (main effect of ear [$F(2,82) = 0.03$, $p = 0.85$, $\eta^2 < 0.001$].

In comparing trials by the tone difference, the large difference condition (*M*= 0.604, *SD*= 0.120), the medium difference condition (*M*= 0.557, *SD*= 0.086) and the small difference condition (*M*= 0.512, *SD*= 0.068) show that the overall scores across participants increases with the tone difference, as the discrimination becomes easier as the difference increases. A repeated measure analysis of variance examining the ear of presentation (LERH versus RELH) and the size of the tone difference (large, medium, or small) found a significance effect across the size of the tone differences [$F(2,82) = 14.01$, $p < 0.001$, $\eta^2 = 0.095$], and Fisher's Least Significant Difference (FLSD = 0.04) indicates that all pairwise differences were significant. The FLSD permits an estimate of the 95% confidence interval range for making pairwise comparisons between means. Results also indicate that only the medium and large difference conditions were significantly greater than one FLSD away from 0.50 chance responding in the binary AXB task.

The interaction of ear of presentation and base tone is presented in Figure 1. If the main hypothesis is correct, the left ear should show better discrimination than the right ear in some or all difference conditions. The left ear performed better than the right ear in the small difference tone discriminations with LERH (*M*= 0.536, *SD*= 0.107) and RELH (*M*= 0.488, *SD*= 0.095), but there was near identical performance in the medium difference condition with LERH (*M*= 0.542, *SD*= 0.099) and RELH (*M*= 0.571, *SD*= 0.121) and in the large difference condition LERH (*M*= 0.599, *SD*= 0.138) RELH (*M*= 0.610, *SD*= 0.141). This interaction effect was significant [$F(2,82) = 3.91$, p = 0.02, $\eta^2 = 0.019$], and FLSD indicates the difference in performance between ears when tone difference was small is significant (0.047 difference > FLSD 0.040), while between ear differences at the medium and large tone differences, show no significant difference between ears as these are more easily discriminated tone differences.

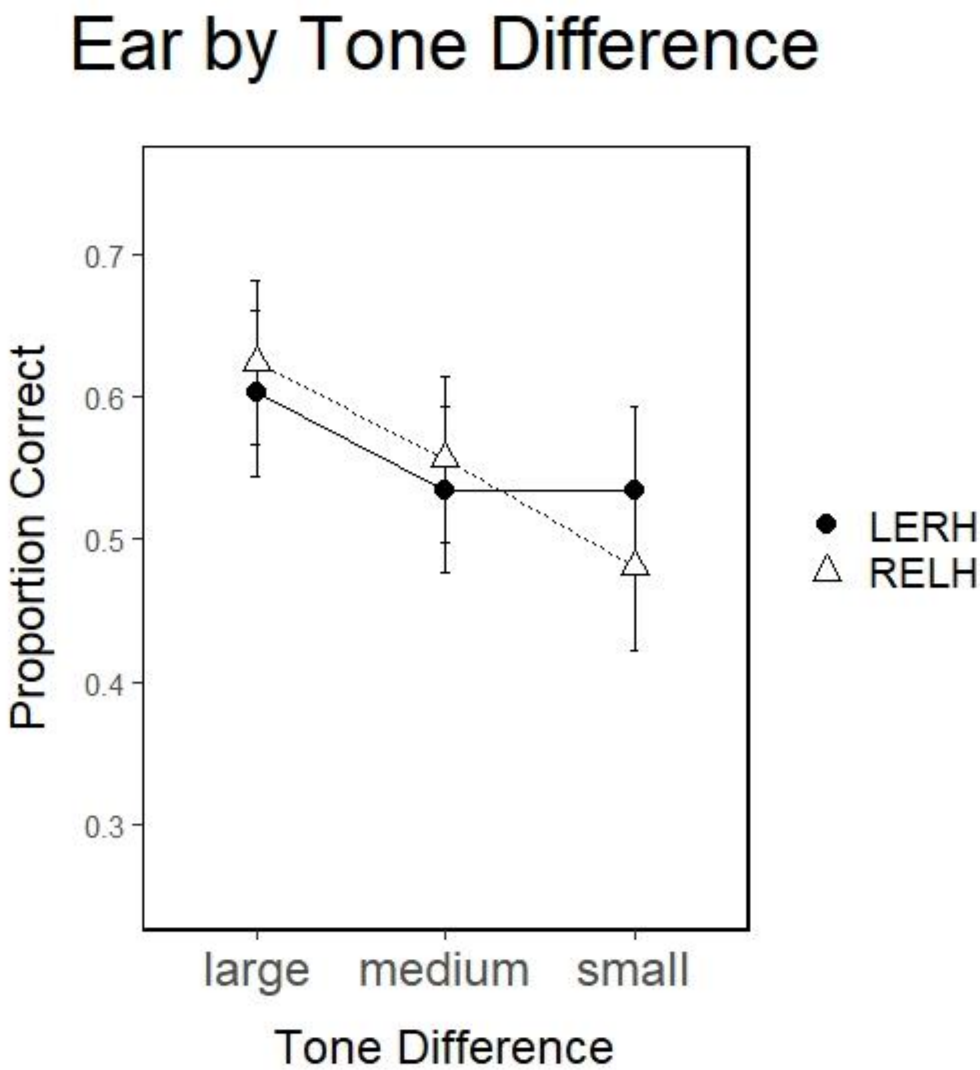

Figure 1. The y axis shows the mean proportion correct for tone identifications and x axis shows the condition of tone difference (large, medium, small). Solid and dotted lines show the ear of presentation, LERH and RELH, respectively. Error bars show 95% confidence intervals based on FLSD.

The next set of analyses examined whether this pattern was consistent within the tone type conditions (low or high tones), repeating the same two-way repeated measures ANOVAs for ear of presentation and tone difference. As shown in Figure 2, similar results were found within the High frequency (1,000 Hz and 2,000 Hz) condition—the main effect of tone difference for discriminations remains significant [$F(2,82) = 6.24$, $p = 0.003$, $\eta^2 = 0.050$] and the interaction effect is only marginally significant [$F(2,82) = 2.44$, $p = 0.093$, $\eta^2 = 0.012$]. Within the Low frequency (100 Hz and 200 Hz) condition, the main effect of tone difference in discriminations again remains significant [$F(2,82) = 10.76$, $p = 0.000$, $\eta^2 = 0.079$], but the interaction is not significant [$F(2,82) = 2.14$, $p = 0.123$, $\eta^2 = 0.014$]. However, a consistent trend of the LERH outperforming the RELH remains present in the data at the small difference condition, seen in both the main Figure 1 and repeated analyses for each tone type in Figure 2.

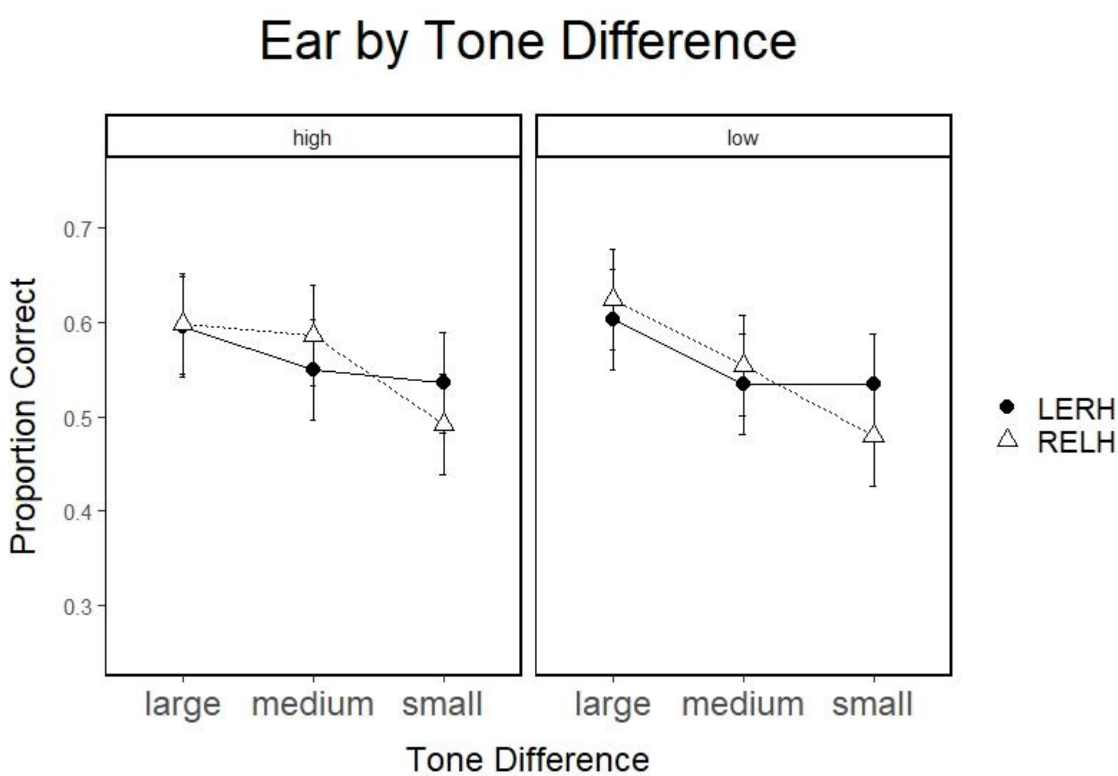

Figure 2. Tone type (high or low) is divided into 2 panels. The y axis shows the mean proportion correct for tone identifications and x axis shows the condition of tone differences (large, medium, small). Solid and dotted lines show the ear of presentation (LERH & RELH). Error bars show 95% confidence intervals based on FLSD.

A three way analysis of variance compared each tone base (100 Hz, 200 Hz, 1,000 Hz, 2,000 Hz), accounting for variation in ear (LERH, RELH) and tone difference (large, medium, small) and shows significance difference among the tone base condition [$F(4,164) = 6.93$, $p < 0.001$, $\eta^2 = 0.054$]. Tone bases near the middle range in the 200 Hz condition (*M*= 0.581 *SD*= 0.113) and 1,000 Hz condition (*M*= 0.592 *SD*= 0.120) show overall a larger proportion correct than tones in the peripheral ranges in the lowest 100 Hz condition (*M*= 0.527 *SD*= 0.080) and highest 2,000 Hz condition (*M*= 0.528 *SD*= 0.082).

The interaction effect found in the collapsing of all data in Figure 1 and trending in high and low tone conditions in Figure 2 seems to be driven by distinctions made in the 1,000 Hz condition, as shown in Figure 3. The other conditions (100 Hz, 200 Hz, 2,000 Hz) show the same trend, but the cross-over interactions for these base tone conditions were not significant, and the LEA at the smallest difference levels were not significant. The 1000 Hz condition is the only condition in which the interaction is significant [$F(2,82) = 3.34$, $p = 0.04$, $\eta^2 = 0.017$]. Moreover, the FLSD indicates that the small tone difference condition in the 1,000 Hz tone base demonstrates the LEA in proportion correct between ears, with performance of the left ear condition significantly greater than chance responding. This indicates a successful replication of the findings reported by Sininger and Bhatara (2012) mirroring the difference in the tone discrimination threshold with the 1,000 Hz tone base.

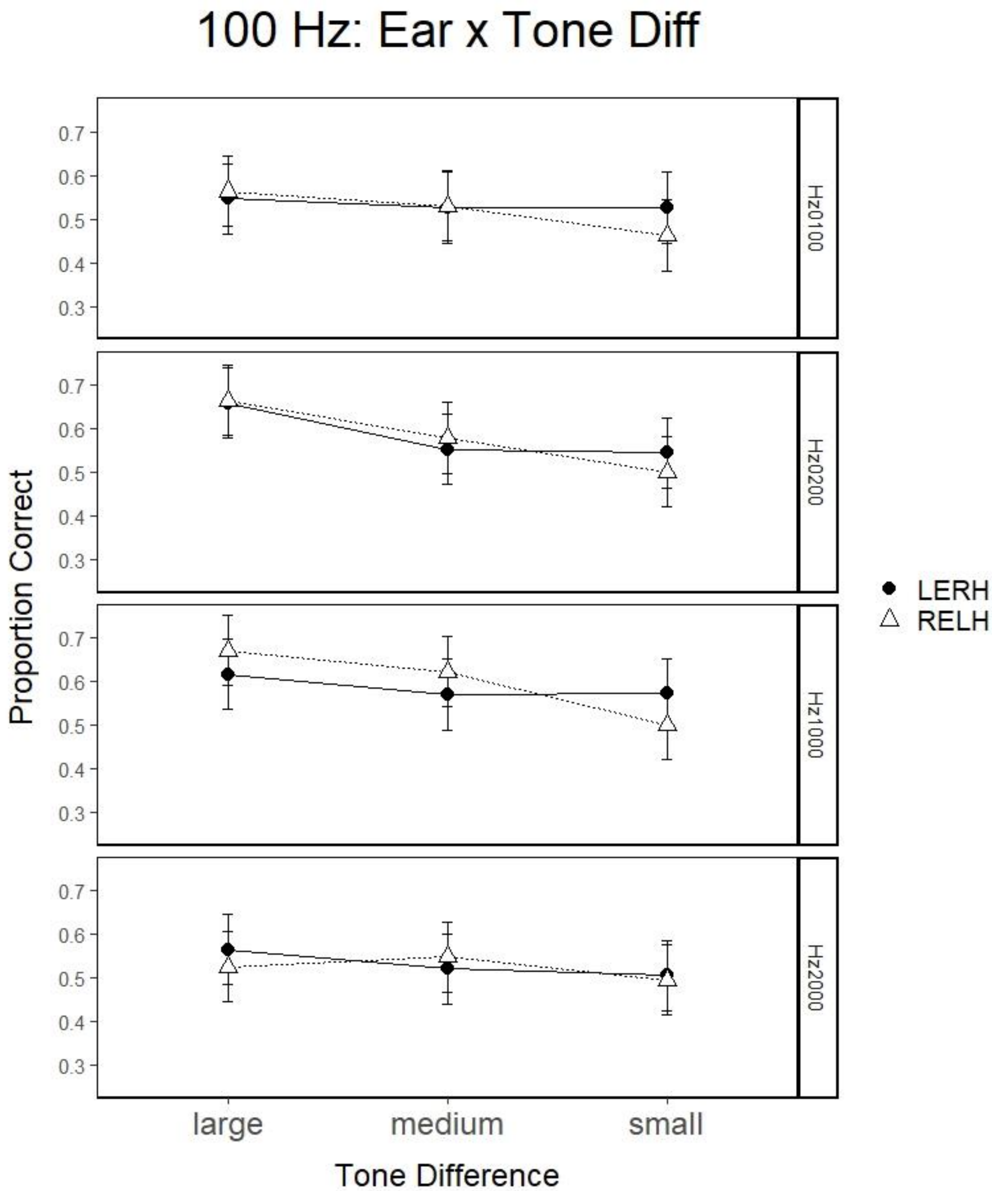

Figure 3. Interaction between tone difference (x-axis) and proportion correct (y-axis) for each ear of presentation displayed within all tone base conditions noted on the right side of the graphs. The y axis shows the mean proportion correct for tone identifications and x axis shows the condition of tone difference (large, medium, small). Solid and dotted lines show the ear of presentation (LERH & RELH). Error bars show 95% confidence intervals based on FLSD.

Discussion

The current study set out to investigate a left ear advantage that would verify a potential hemispheric asymmetry in pitch processing. Replicating and extending Sininger and Bhatara (2012), more tone bases were explored, specifically below and between the frequencies tested to include the current study's use of 100 Hz and 200 Hz, replicating the 1,000 Hz condition, and a measure at 2,000 Hz. In this way, the range of the LEA could be further tested to observe whether this effect was prominent in other parts of the frequency range. The degree of tone difference, as in distance from the tone base, also assumed multiple conditions (small, medium, and large) to ensure a general idea of magnitude among each tone base and type.

The hypothesis for the universal presence of a LEA among all frequency groups and tone difference conditions is limited within this specific study design. The ear of presentation, LERH and RELH pairs, show no significant difference when collapsed along tone bases and difference conditions. The magnitude of tone difference demonstrates a significant result in influencing the proportion correct as this indicates the degree of difficulty of the tone discrimination. The small tone difference condition indicates a LEA, demonstrating a significant difference in discrimination between the ears, however, collapsed across all tone bases, the lower scores are not significantly different from chance responding as their difference is lower than the FLSD from a 0.50 score. The medium and large tone differences perform above chance when collapsed across all tone bases, however, there was a lack of a significant difference between the ear of presentation.

The difficulty of the small tone condition, for example, shows within chance responding in the lower 100 Hz. This difference between 100 Hz and 101 Hz is very near undetectable but serves as the strongest test in the experimental design. If the LEA is to be found, it would be in this smaller, more difficult to discern pitch discriminations and not present within the more detectable and easier high tone difference. As seen in the data, the larger tone discriminations end up showing more similar scores among the ear of presentation due to their relative ease in detection and do not prove to be a good measure for detecting the presence of the LEA. However, in the case of the 100 Hz and 200 Hz conditions, the small differences (1 Hz and 2 Hz) appear to have been below threshold for both left and right ear presentations.

Performing this test for each tone base, the effect of tone difference and ear can be further investigated to observe if the LEA is present within specific ranges. A successful replication of Sininger and Bhatara (2012) verifies the original findings of a LEA within in the 1,000 Hz frequency range. The small difference condition for this tone base was at 5 Hz in the current study, very near threshold for the left ear and below threshold in the right ear (as reported in Sininger and Bhatara, 2012). Therefore, the small difference condition in the current study was primed to capture this significant difference that was successfully replicated between the two ears. The largest difference between the ear of presentation is found within this condition. This is demonstrated by the significant interaction present in the data, observed only in the 1,000 Hz tone base. In this condition, the LERH and RELH scores significantly differ from one another, and only the LERH was also significantly above the FLSD for chance responding, comprising replication of the previous study's findings.

When separated by tone type, high versus low tones, there is a slight persistence of the interaction effect, showing a trend in the other tone bases. Furthermore, the significant effect of tone base demonstrates that the proportion correct is differing according to the frequency tested and not as universally present. When collapsed across all tone differences, higher means are observed in the 200 Hz and 1,000 Hz conditions, perhaps inferring that these more acute tone perceptions may reflect aspects of processing superiority in the right hemisphere being limited to specific bands of frequency that have the possibility for displaying the LEA. Alternatively, it could be the case that the magnitude of the small differences used in the 200 Hz and 1000 Hz conditions were closer to the actual discrimination thresholds for these tones, while those in the 100 Hz and 2000 Hz conditions were below thresholds.

The sensitivity of the human ear to this spectrum near 1,000Hz, which drives the current study's interaction effect and laterality for pitch processing, may be a governing piece for the recognition of speech formants which cue the listener to the articulation of words. Zattore (2012) showed that passive speech listening leads to bilateral activation in the superior temporal lobe, with both hemispheres equally active compared to active speech listening which showed activation of the left lateralized speech areas. When asked to determine whether pitch is changing within a word-phrase, this distinction leads to the activation of the right inferior frontal gyrus, suggesting that tone discrimination as a lateralized neural sub-system should not be not frequency limited to 1,000Hz or other tone distinctions as seen in the data. This implies that both hemispheres are registering tones and speech sounds until discrete judgements must be made by the left hemisphere which becomes active in the extraction of these components.

The Frequency Following Response denotes that neural activations occur at the same rate in tandem with the peak amplitudes of frequency waves (phase-locked). This is how changes in pitch are encoded in the brain (Coffey, Nicol, White-Schwoch, Chandrasekaran, Krizman, Skoe, Kraus, 2019). The volley principle states that a synchrony of neural firing where phase-locking is not possible may allow for frequencies above 1,000 Hz to be shared among neural groups for encoding higher frequencies. For example, when 5,000 Hz is encoded in the geniculate body with a 800 Hz firing rate. This may explain the drop-off in perceived loudness or signal strength after the 1,000 Hz threshold where the new method encoding is utilized as seen in the equal loudness contour (Appendix B). This may also be a potential explanation for the asymmetric differences found in pitch processing in the current experiment. Perhaps the exact differences between left (LERH) and right (RELH) ear pairs is most distinct near this threshold where difference can be compared in the discrepancies between the ear prior to the involvement of more complicated neural groupings seen with the volley principle.

The current study using sine waves in tone presentation yields a significant LEA only within the 1,000 Hz condition for small tone discriminations but does show a trend among all tones. The limiting of the advantage found may be relevant to the type of wave synthesis. It is known that square wave pitches show an enhancement of the LEA findings for pitch discrimination (Mathiak, Hertrich, Lutzenberger, & Ackermann, 2002), and with a larger sample size, the trends for the current study may have found significance within the other tone bases. The addition of the paired white noise in the opposing ear may have also interfered in tone discrimination becoming more significant as seen in other studies (Tenke, Bruder, Towey, Leite, & Sidtis, 2007). In both regards, the type of wave oscillation or to signal conflicts from the opposing ear could have made tone discrimination difference less distinct.

Limitations & Future Studies

Lateralization is understood and verified to exist within linguistic processing due to the need for the extraction and secondary auditory regions to interpret sounds into their semantic inferences. The LEA for the lateralization of pitch processing, from the gathered data, seems to have a lesser degree of magnitude and universality than the REA for linguistics. The current study demonstrates how the presence of the LEA is limited within small tone difference discriminations and only detectable within a limited range of frequencies or tone bases.

Continuing study may be able to employ frequencies near to the 1000 Hz range which demonstrated the largest effect (800 Hz, 1200 Hz), perhaps making it easier to catch the depth of phenomenon in human hearing. As well, concerning the magnitude of difference, the lesser small tone distinctions should also be utilized with further studies as this is most accurate for displaying a difference between the ears. Ideally, an experiment design can use a small difference condition ubiquitously and rather lead the testing to different frequency conditions or multiple tone bases. Future studies should use more closely related parameters for tone discrimination with baseline frequencies that are verified for displaying the largest effects. Then the testing of multiple other tone bases can be performed to understand the scope and breadth of this phenomenon. Although the pitch processing asymmetry appears less universal then the REA for linguistic distinctions, this will ensure capturing the LEA along the frequency spectrum which is less present when dealing with larger tone discriminations.

Many other factors have been hypothesized to influence the processing of pitch such as the degree of musical training or handedness; however, the current study did not include enough appropriate participants to allow for testing of these aspects. Musical training is believed influence the processing of pitch towards more bilateral processing and equal ability of pitch discrimination in both ears (Behroozmand, Ibrahim, Korzyukov, Robin, & Larson, 2014). If this information could have been factored in, a correlative measure could have been devised to observe differences in these measures of laterality in the general public and musically trained individuals as well as how this affects their overall proportion correct. Presumably increased performance and equivalent ear scores would be found in the more musically trained individuals.

Handedness is said to influence the way pitch processing occurs due to structural and functional changes in the brain. Right-handed persons tend to have language lateralized to their left hemisphere, moving other functions such as pitch to the right hemisphere. The converse has been observed in those who are left-handed, in that they may represent language on their right hemisphere, moving pitch to the left hemisphere (Bear, Connors, Paradiso, 2007). This would change the interpretation of the data to give another layer of accuracy in predicting an ear of advantage in a right or left handed individual in the conditions (1,000Hz small difference) that displayed the hemispheric advantage. Importantly, this alternative is less likely in the present study because we ascertained handedness with only 2 participants in the study self-reported as left handed.

Another potential distinction is that males were found to demonstrate more laterality than their female counterparts (Shaywitz, et al. 1995), adding another potential level of difference in the degree of ear-hemisphere advantage. Female counterparts would then be hypothesized to display less laterality or difference between ears than men. However, this study showing a disproportionate representation sex (9 males and 33 females) does not allow for a meaningful analysis of sex differences.

Conclusions

The current findings demonstrate that the left ear proportion correct is also more robustly stable between the small and medium difference conditions, maintaining close to equal proportions, whereas the right ear displays the trend of a decreasing slope between the proportion correct and the increase of tone difference (a negative correlation). This may be a calling card for the presence of LEA, where a protocol can be developed, not in the difference of the overall proportion correct but in the robustness of the scores (slope) across difference conditions, seen in the LERH. A magnitude for the rate of deterioration between small and medium differences can be indicative of the present advantage between the two ears and allow for easier detection of the

LEA in frequency bands where it may be more subtle. This gradient and change of gradient can then be mapped for understanding thresholds within human hearing.

As the current study demonstrates, the magnitude of difference interacts among tone bases, therefore testing within multiple tone bases in a small difference condition would allow for a general view on how laterality changes across the frequency spectrum. A trend towards small tone discriminations is found when collapsed across all frequency ranges that corroborates the findings of Sininger and Bhatara (2012) that the LEA is present within the 1,000 Hz tone base at the small tone difference condition.

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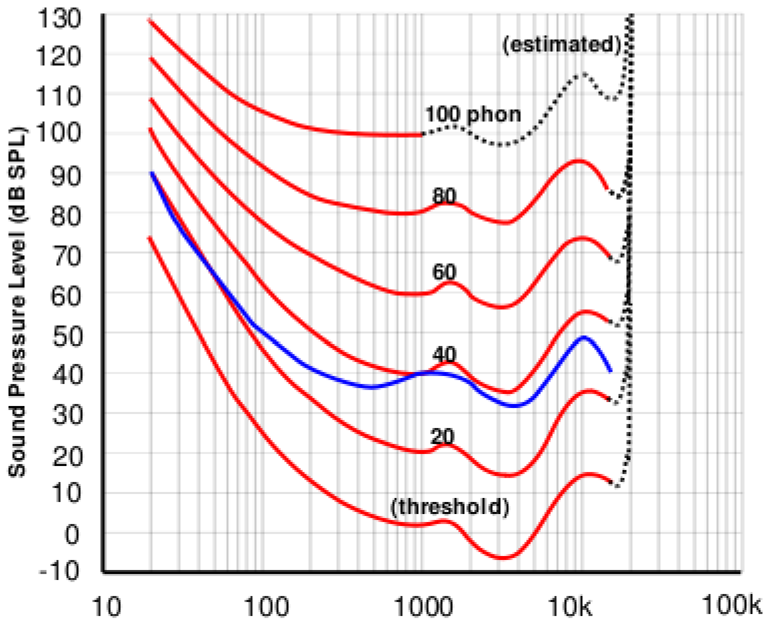
Appendix A

Base Frequency	Increase/Decrease Freq	Difference Frequencies
100 Hz	1, 2, 3 Hz	97, 98, 99 // 101, 102, 103
200 Hz	2, 4, 6 Hz	194, 196, 198 // 202, 204, 206
1,000 Hz	5, 10, 15 Hz	985, 990, 995 // 1005, 1010, 1015
2,000 Hz	5, 10, 15 Hz	1985, 1990, 1995 // 2005, 2010, 2015

Appendix B



Equal-loudness contours (red) (from ISO 226:2003 revision)
Original ISO standard shown (blue) for 40-phons