The Impact of Simulated High- and Low-Frequency Hearing Loss on the Phonetic Context Effect

by

Amanda Michelle Monaco

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This thesis was presented

by

Amanda Monaco

It was defended on

April 7th, 2017

and approved by

Christopher Brown, Ph.D., Communication Sciences and Disorders, University of Pittsburgh

Andrew Lotto, Ph.D., Speech, Language, and Hearing Sciences, University of Florida

Erin Lundblom, Ph.D., Communication Sciences and Disorders, University of Pittsburgh

Thesis Advisor: Sheila Pratt, Ph.D., Communication Science and Disorders, University of Pittsburgh

THE IMPACT OF SIMULATED HIGH-AND LOW-FREQUENCY HEARING LOSS ON THE PHONETIC CONTEXT EFFECT

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This study assessed whether young adults demonstrate the phonetic context effect under conditions of normal hearing, and simulated low-frequency and high-frequency hearing loss. Twenty normal hearing participants, aged 18 to 25, listened to 600 disyllables that included a natural /ar/ or /al/ followed by a synthesized consonant-vowel (CV) syllable from the /ga/-/da/ acoustic continuum. Ten different CV syllables were constructed so that the onset of the third formant (F3) ranged from 1800 to 2700 Hz in 100 Hz steps. Each disyllable was processed to reflect normal hearing, a low-frequency hearing loss and a high-frequency hearing loss. The disyllables were presented in random order, and after each presentation, participants were asked to indicate if the last syllable was a *ga* or a *da*. Using Probit regression and Poisson analyses, the results showed that in the normal hearing condition the participants demonstrated the context effect as reflected by hearing more *ga* syllables in the context of /al/ than /ar/. In the low-frequency condition the average identification function was shallow with half of the participants failing to show clear categorical boundaries, but of those that did, 9 of 10 demonstrated a context effect. In the high-frequency hearing loss condition the participants failed to show any distinct categories or clear sensitivities to the /ar/ and /al/ contexts.

These results have implications for people with hearing loss and how their hearing losses are treated. The results suggested that even a moderate high-frequency loss can interfere with categorical perception and use of contextual cues. Moreover, a moderate low-frequency hearing loss, which often is overlooked for treatment, may interfere with speech processing in some people.

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PREFACE

The completion of this project would not have been possible without the generosity of Dr. Sheila Pratt. Thank you for the time you spent assisting me, teaching me, and working with me, despite your many other obligations. I will be forever grateful for the knowledge you have imparted on me. Financial support for this project was provided by the University of Pittsburgh Honors College.

1.0 INTRODUCTION

Speech sounds are rarely produced in isolation, but rather in a continuously overlapping manner. As a result, speech gestures interact, and the acoustic cues reflect this interaction and variability over time, space, linguistic context, and individual speakers. This variability has long been a challenge for researchers looking for invariance and identifiable patterns, with the goal of relating it to how listeners are able to extract usable cues, and perceive and use speech acoustic information for communication. Many researchers currently believe that listeners recover coarticulation by attending to the context (acoustic and otherwise) and the associated relational properties of ongoing speech. This approach to perception has implications for people with hearing loss where spectral information and speech cues can be absent, inconsistently present, reduced in intensity, distorted, and altered by their sensory devices.

1.1 COARTICULATION

Speech and its production is largely considered a serial process, although parallel processes are evident in the coordination of speech gestures as they overlap in time and space (Guenther, 1995; Kent & Moll, 1972). This overlap is referred to as coarticulation, and has implications for the acoustic properties of speech and how we hear speech as it unfolds over time (Lotto & Kluender, 1998).

Coarticulation varies by individual speaker, age, language, articulation rate, vowel stress, prosody, phonotactic constraints, and phonetic context (Beddor, Harnsberger, & Lindemann, 2002; Cho, 2004; Guenther, 1995; Kent & Moll, 1972; Magen, 1997; Matthies, Perrier, Perkell, & Zandipour, 2001; Zharkova, Hewlett, & Hardcastle, 2011). For example, Daniloff and Moll (1968) found that in English sentence-level productions, the influence of lip-rounding and protrusion was evident in four to five sounds preceding the vowel /u/ (anticipatory or forward coarticulation). Moreover, the influence crossed syllable and word boundaries, and articulatory targets were rarely met. Benguerel and Cowan (1974) observed a similar effect for lip protrusion associated with the French vowel /y/ when preceded by a series of blends (e.g., “une sinistre structure”), where the vowel influence could be seen on the two preceding blends (/strstr/) and sometimes even on the vowel before the blends. It also has been shown that vowels can influence the spectral energy distribution of the release transient and the release burst and vowel transition in consonant-vowel (CV) productions (Blumstein & Stevens, 1980; Cullinan & Tekieli, 1979; Repp & Lin, 1989; Winitz, Schreib, & Reeds, 1972).

The impact of coarticulation also is observed with succeeding sounds, which is referred to as carryover, perseverative, or backward coarticulation. For example, bilabial consonants impact the lip opening for following vowels, and initial nasals impact the spectral characteristics of subsequent vowels and consonants (Fujimura, 1961). In English, perseveration tends to be more common and has a greater influence than anticipatory articulation (Fowler, 1981, Gay, 1974; Parush, Ostry & Munhall, 1983), although in natural ongoing speech the influences are multi-directional.

Vowels and liquids have particularly strong coarticulatory effects, with both sound types producing pronounced local and distant effects. Vowel context has been shown to affect exact place of articulation of stop consonants (Gibbon, Hardcastle, & Nicolaidis, 1993; Öhman, 1966) and the English liquids /l/ and /r/ are known to shift the frequency emphasis of adjacent and distant consonants and vowels (Kochetov & Neufeld, 2013; West, 2000).

Although a discussion of the neuro-motor operations needed to produce ongoing speech is beyond the scope of this paper (Bohlanda & Guenther, 2006; Hickok & Poeppel, 2004; Tourville & Guenther, 2011), it is worth noting that some impairments of speech production, such as apraxia of speech and speech impairment secondary to hearing loss, are associated with breakdowns in coarticulation and reduced intelligibility (Deger & Ziegler, 2002; McNeil, Hashi, & Southwood, 1994; Pratt & Tye-Murray, 2009).

1.2 PHONETIC CONTEXT EFFECT

As indicated above, phonetic context contributes to coarticulation and the resulting acoustic cues are used in and affect the auditory perception of speech. Wolf (1978) and Summers (1988) found that spectral differences in the early part of low vowels were used by American English listeners to predict the voicing of syllable-final consonants. Mann (1980) assessed the influence of /r/ and /l/ on the perception of subsequent /d/ and /g/ sounds. By pairing /al/ and /ar/ vowel-consonant (VC) syllables with synthetic consonant-vowel (CV) syllable tokens reflecting the /ga/-/da/ acoustic continuum, she found that listeners perceived /ga/ more often when preceded by /al/ than /ar/. In isolation, /d/ has a more forward place of articulation at the alveolar ridge than /g/, which is typically articulated posteriorly towards the velum. As a result, /d/ has a higher F3 onset frequency than /g/, but when produced in the context of /al/ and /ar/, the F3 onsets are more similar and the spectral differences decrease substantively. Despite this lack of spectral distinction, listeners appear to compensate for these effects. Even though the syllables that follow /al/ acoustically resemble /da/, listeners tend to hear and label them as /ga/, attesting to the ability to perceptually compensate for coarticulation.

Lotto and Kluender (1998) expanded upon this line of research to test whether recovery of coarticulation is based on articulatory gestures or dependent on general auditory processes. They measured the perceptual impact of naturally produced /al/ and /ar/ syllables (male and female) on synthesized /ga/-/da/ syllables, with the continuum based on third formant (F3) onset frequency manipulation. Their results were similar to those of Mann (1980) for both the male and female antecedent syllables. The results were replicated with frequency-modulated sine waves (modeling the different F3 characteristics of the /r/ and /l/) as the preceding context, and then with constant sine waves with the offset F3 frequency of the natural /al/ and /ar/ sounds. The authors argued that the context effects were likely due more to general auditory processes than articulatory dynamics, because the results were not dependent on the inherent vocal tract dynamics of the male and female speakers, or tonal non-speech stimuli (Lotto & Kluender, 1998).

In a similar approach, Holt, Lotto and Kluender (2000), assessed the impact of stop consonant spectral context on vowel perception. Initially, categorical perception along the /ɛ/-/ʌ/ continuum was assessed with the vowel samples imbedded in /b/-Vowel-/b/ (bVb) and /d/-Vowel-/d/ (dVd) syllables. In additional experiments, FM-glides and tones replaced the transitions and steady-state portion of the vowels. They also replaced /b/ and /d/ with /p/ and /t/ respectively, to examine the impact of consonant voicing. Holt et al. found that the vowels in the /dVd/ context were labeled as /ʌ/ more often than in the /bVb/ context. Similar results were observed for the glides and tones indicating that on some basic level, speech sounds are treated by the auditory system in the same manner as non-speech sounds of similar spectral content. The results also suggested that spectral contrast, and not phonetic labeling, contribute substantively to vowel identification. Holt and colleagues (Stephens & Holt, 2003; Lotto, Sullivan, & Holt, 2003) further examined the abilities of listeners to use spectral contrast when listening to speech and non-speech analogues. The results of these studies were largely supportive of the argument that the auditory system processes relative acoustic patterns over time and not speech gestures per se.

1.2.1 Animal and Infant Studies

Animal perceptual studies have long been used to demonstrate that certain abilities are basic functions and not necessarily attributable to humans or specialized mechanisms. For example, Kuhl and Miller (1978) and Kuhl (1981) demonstrated that chinchillas can discriminate voice-onset-time in CV syllables in a manner reflecting categorical perception. Lotto, Kluender, and Holt (1997) similarly used Japanese quail to demonstrate that sensitivity to spectral contrast was a general auditory process. They trained four quail: Two with CV syllables with low F3-onset frequencies (/ga/), and the other two with CV syllables with high F3-onset frequencies (/da/). After successful training, the birds were presented a series of /da/-/ga/ syllables in the /al/ and /ar/ contexts. The birds trained to peck to /ga/ responded *ga* more often in the context of /al/ than in the context of /ar/, and the birds trained to peck to /da/ responded *da* more often in the context of /ar/ than /al/. The results were similar to those found with humans and suggested that the impact of phonetic context is species general rather than specific, yet the role of training was a potential confound.

Similarly, the results from infant perceptual studies have been used as evidence to argue against mechanisms that require exposure or training. Young infants have limited experience with coarticulated speech, and coarticulation is not stable in children's productions until later childhood, yet they demonstrate a perceptual sensitivity to phonetic context and an ability to compensate for coarticulation. Fowler, Best and McRoberts (1991) tested 4- and 5-month-old infants with a habituation-visual-fixation paradigm and found that like the adult studies, there was a shift in boundary of discrimination in a context-sensitive manner (more /g/ responses following /l/ than /r/). Given the age of these infants and the research showing that young infants have strong pattern perception skills (Aslin, Saffran & Newport, 1998; Thiessen & Saffran, 2003), these findings could be used to argue for a general auditory process or cognitive abilities to detect relative distributional properties of the sounds. However, Fowler et al. (1991) argued that the data supported a more gestural accounting of perception. Fowler (1996; 2006) has suggested that in the process of hearing speech, listeners recover invariant speech gestures from the acoustic signal rather than process the relative acoustic patterns presented in the acoustic signal. That is to say, it is not general auditory processes that are responsible for the perception of speech sounds, but rather the direct perception of gestures.

The manner by which acoustic signals are used by the auditory system for speech perception has implications for people with hearing loss. From a gestural perspective, it would be important to know what needs to be present in an acoustic signal to activate the correct gestures. Auditory and cognitive approaches would find it important to know the importance or weights of acoustic patterns within and across parameters, and how easily they can be reorganized in the face of absent, inconsistent, altered or distorted signals.

1.3 HEARING LOSS

In the United States, 29 million Americans (roughly 16% of the population) suffer from hearing loss, and 8.5% of young adults aged 20-29 exhibit hearing loss (Agrawal et al., 2008). The number of Americans exhibiting hearing loss is expected to increase as the population ages. Age-related hearing loss tends to be sensorineural, high-frequency and bilateral. It is associated with reduced speech recognition and discrimination, particularly in background noise and adverse listening conditions (Bilger & Wang, 1976; Boothroyd, 1984; Moore, 2003). Low-frequency and flat hearing loss configurations are less common and typically have less impact on speech perception. More generally, the more severe the hearing loss, the greater the impact on speech perception (Boothroyd, 1984). Vowel perception tends to be more resistant to hearing loss than consonants, with consonant place cues being more impacted than manner cues followed by voicing cues (Walden & Montgomery, 1975; Bilger & Wang, 1976). In general, the perception of speech sounds that are brief, and of low intensity and high-frequency are susceptible to hearing loss.

The primary impact of hearing loss is reduced availability of the acoustic signals. Loudness recruitment, impaired frequency selectivity, and associated distortions also contribute to poor perception of speech. The perception of speech in noise can be impacted by changes in the auditory filter bandwidth as well. Most adults with hearing loss do not seek treatment (e.g., hearing aids, cochlear implants, auditory training) until the loss compromises their ability to communicate effectively. In the United States, only 39.5% of adults, aged 70 years and above, have had their hearing tested even though hearing loss is nearly ubiquitous with aging (Neiman et al., 2016). Furthermore, only 14.2% of all people in the United States with hearing loss wear hearing aids (Chien & Lin, 2013). The use of hearing aids largely is dependent on hearing loss severity, with only 3% of people in the United States with mild hearing loss wearing hearing aids, followed by 40% with moderate loss, and 77% with severe hearing loss. Although hearing aids compensate by amplifying signals and thus providing improved audibility, many people with hearing loss continue to have difficulty understanding speech (Phatak et. al, 2009).

2.0 HYPOTHESIS

The aim of the study was to determine the extent to which moderate low- and high-frequency simulated hearing losses impact the ability of young adult listeners to use spectral contrast in the identification of speech. As such, the experimental questions were:

- Will a typical high-frequency hearing loss influence the phonetic context effect previously shown in normal hearing listeners for /da/- ga/ syllables when preceded by /al/ and /ar/ syllables?
- Will a mirror-image low-frequency hearing loss influence the phonetic context effect previously shown in normal hearing listeners for /da/-/ga/ syllables when preceded by /al/ and /ar/ syllables?

It was considered likely that high-frequency hearing loss would either eliminate or reduce the effect of spectral contrast because the prominent distinguishing cues for all the syllables were high in frequency. The low-frequency hearing loss would not likely eliminate the effect because the high-frequency speech cues were retained, but the effect could be reduced because of reduced overall intensity (most power in the speech spectrum is in the low-frequency range), and the F1 formant transitions provide secondary cues for naturally produced /l/ and /r/.

The F2 frequencies also provide context effects, and this could be impacted by a low frequency-hearing loss. These lower-frequency cues could be operational for normal hearing conditions, along with the high-frequency cues targeted by this study.

3.0 METHODS

This study was comprised of two sessions. Screening for participant inclusion and exclusion was completed during the first session. The experiment was conducted in the second session. Participants listened to CV syllables along the /ga/-/da/ acoustic continuum immediately after hearing /ar/ or /al/. They completed this experiment under normal hearing, high-frequency hearing loss and a low-frequency hearing loss condition.

3.1 PARTICIPANTS

The University of Pittsburgh IRB approved this study and all participants provided written and oral informed consent before participation. Participants aged 18 to 25 years were recruited through announcements and fliers. They received $10 upon the completion of their second session. Twenty-two participants were enrolled in the study but two were excluded – one due to failure to return for the second session; the other failed to qualify. All the participants had normal hearing, were native speakers of English, and had no history of speech/language or academic problems. They all had completed high school and were currently undergraduate students enrolled at a university.

Table 1. Participant Demographic Information

Participant	Demographic Characteristics		
ID Number	Age	Race/Ethnicity	Sex
034603	21	Caucasian	M
68133	21	Caucasian	F
277848	22	Caucasian	F
036662	20	Hispanic and Caucasian	F
524176	22	Indian	F
440741	22	Caucasian	F
118761	20	Caucasian	F
330906	22	Caucasian	F
213933	21	Caucasian	F
618245	21	Mixed	M
152654	22	Caucasian	M
182309	21	Caucasian	F
305193	21	Caucasian	F
901068	21	Caucasian	F
087351	22	Caucasian	F
239635	21	Caucasian	M
743979	21	Caucasian	F
93803	21	Caucasian	F
562324	21	Caucasian	F
956217	19	Caucasian	F

During the first session, the participants completed a background questionnaire, tympanometric screening of middle ear function (ASHA, 1990), and a standard puretone hearing threshold test at 1000, 2000, 4000, 8000, 250, and 500 Hz (ASHA, 2005). The puretone threshold test was completed in a sound booth with insert earphones (ER-3A) and a diagnostic audiometer (GSI 12). Puretone thresholds needed to be 25 dB HL or better at all test frequencies. Word recognition also was assessed under insert earphones with the Northwestern University Test # 6 (NU-6; Tillman & Carhart, 1966) wordlist presented at 40 dB SL re: puretone average. The Auditec male voice recording of the NU-6 was used, with 25 items presented to each ear. The word recognitions scores needed to be 92% or better for both ears.

3.2 STIMULI

The stimuli consisted of VC_CV disyllables constructed after Lotto and Kluender (1998). The VC components consisted of natural productions of /al/ and /ar/. Natural samples were used because they are more resistant to hearing loss than synthesized samples and because they likely included secondary speech cues that could influence perception under the hearing loss conditions. The VC syllables were produced within the phrase “say __again” by a male speaker. The recordings were done in a sound booth with a microphone (Shure SM58) and digital recorder (Marantz PMD 661MKII). The recordings were then transferred to a sound editor (Adobe Audition CC) to excise the samples, edit length to 250 ms and adjust the average RMS intensity to match that of the synthesized unaltered CV syllables.

Ten CV syllables were synthesized with a Klatt parametric synthesizer (HLsyn, v2, Sensimetrics) with parameters set to reflect the /da/-/ga/ acoustic continuum and matched to those used by Lotto and Kluender. The 10 syllables varied by F3 onset frequency from 1800 to 2700 Hz in 100 Hz intervals. They were constructed with a transition of 80 ms shifting linearly from onset to a steady-state of 2450 Hz. The remaining parameters remained constant across the CV syllables. The F1 and F2 had onset transitions of 80 ms with the F1 shifting from 300 Hz to a steady state of 750 Hz, and the F2 from 1650 Hz to a steady state of 1200 Hz. The F0 was set at 110 Hz and then decreased to 95 Hz during the final 50 ms of the syllable. The overall duration of all syllables was 250 ms. Each of the CV syllables were then appended to the /al/ and /ar/ VC syllables with a 50 ms interval between the syllables. The beginning and ending of each VC_CV disyllable was bounded by a 50 ms silent interval. The samples were then up-sampled from a 11.025 kHz rate to 44.1 so that the rate would be compatible with that of the hearing loss simulator.

To simulate the hearing loss, the VC_CV disyllables were processed through a hearing loss simulator (HeLPS v2, Sensimetrics) that used a fast-acting, level- and frequency-dependent amplitude compression algorithm to introduce attenuation and loudness recruitment (Zurek & Desloge, 2007). The syllables were processed to introduce a moderate high-frequency hearing loss to both ears that simulated the average hearing loss of the 60-64-year-old male group from Cruickshanks et al. (1998). Then the original disyllables were processed again for a mirror-image low-frequency hearing loss. The hearing configurations are shown in an audiogram below (Figure 1) and sample spectrograms of the hearing loss effects in the Appendix section. The overall amplitude of the signals was adjusted to account for processing loss previously noticed when calibrating the software output. Previous work in the mentor's lab had shown that the simulator was largely on-target after correcting for this loss and that it produced expected detection thresholds and sound confusion patterns on the NU- and the California Consonant Test (Owens & Shubert, 1977).

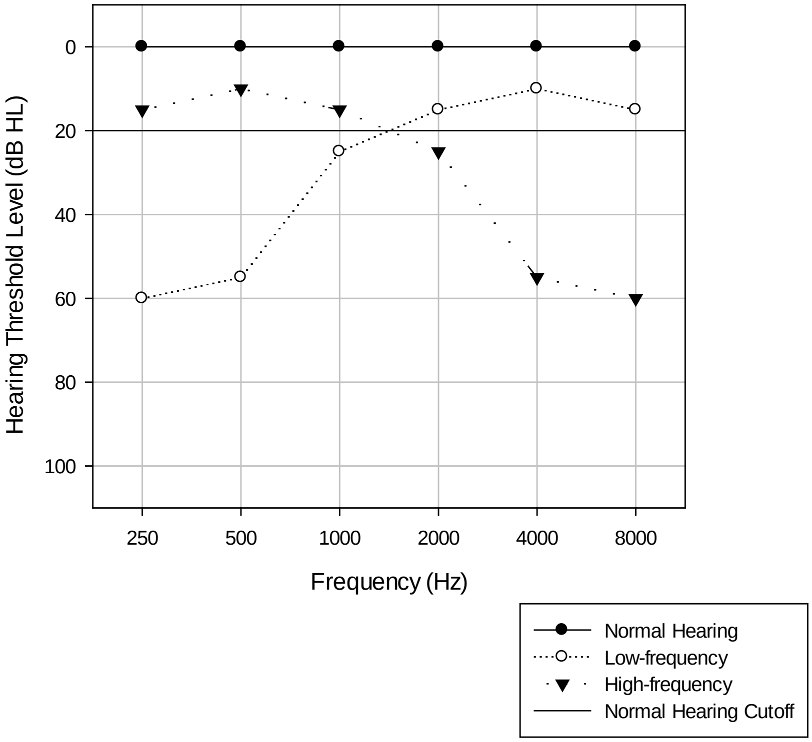

Figure 1. Simulated hearing loss configurations

3.3 PROCEDURES

Upon completion of the first session, participants returned for a second visit to complete the experimental procedures. They were first introduced to the normal 1800 Hz and 2700 Hz CV syllables to familiarize themselves to the synthetic nature of the stimuli. Then the participants were screened with two instances of the normal 1800, 1900, 2600, and 2700 Hz CV syllables presented in random order. This was done to document ability to identify synthesized exemplars. The participants had to identify six out of eight CVs correctly to proceed to the experimental task. Only one participant failed to reach this criterion on the first try but did so when the screen was re-administered.

The experimental protocol was administered via SuperLab 5 software. The stimuli were routed from a desktop computer, amplified by an audiometer (GSI 12) and then presented to the participant via insert earphones (ER-3A) with the participant seated in a sound booth. The intensity was set so that the normal hearing stimuli were presented at 65 dB SPL. Each VC_CV combination (2 contexts x 10 F3 onset frequencies x 3 hearing conditions) was presented 10 times each in random order, resulting in 600 trials per participant. The participants were asked to press a button on a response pad to indicate whether they heard *ga* or *da*. After 200 consecutive trials, a 5-minute break was given.

4.0 ANALYSIS

A Probit regression analysis was completed to compare categorical boundary locations per context (/al/ vs. /ar/) and simulated hearing loss condition. Furthermore, 1800 and 1900 Hz stimuli also were excluded from the analysis due to an error when constructing the stimuli. This made the range on the continuum 2000-2700 Hz.

A second analysis was conducted because the high-frequency hearing loss condition eliminated the observable categorical boundaries. To account for the high-frequency hearing loss condition the count of *ga* responses was divided into low- and high-frequency bins (divided between 2300 and 2400 Hz) along the /ga/-/da/ acoustic continuum, and a Poisson analysis was applied to compare the average counts of *ga* responses in the low- vs. high-frequency regions of the /ga/-/da/ continuum per context and simulated hearing loss condition.

5.0 RESULTS

The Probit regression showed a significant difference in the perceptual boundaries for /ar/ and /al/ in the normal hearing condition, *F*(1)=13.86 and *p*=.002. There was a greater tendency to hear *ga* after /al/ than /ar/ (/ar/ *mean*=2296 Hz, *SE*=23; /al/ *mean*=2425 Hz, *SE*=30). This can be seen in Figure 2 where the boundary for the /al/ context shifted higher in frequency relative to the /ar/ context. On both functions, there was a noticeable bump at 2500 Hz, especially in the /al/ context. This deviation likely was due to the F3 transition of the second syllable being flat at 2500 Hz and matching the frequency of the F3 of the /l/, which also was relatively flat. This lack of distinction may have caused some confusion when the two syllables were paired.

In the low-frequency hearing loss condition, no significant difference was found, *F*(1)=.18, *p*=.681; /ar/ *mean*=2415 Hz, *SE*=51; /al/ *mean*=2384 Hz, *SE*=58. This lack of difference was likely due to 10 of the participants not demonstrating a clear categorical boundary in this condition. Of the 10 who did show a boundary, 9 responded with more *ga* responses in the /al/ than /ar/ contexts. Because of the mixed nature of the responses it was not surprising that the average identification function (Figure 3) for the low-frequency hearing loss condition was shallower than that from the normal hearing condition. As indicated above, there was no valid boundaries for the high-frequency hearing loss condition, so no boundary comparison occurred under that condition.

Figure 4 shows that the average identification function for the high-frequency hearing loss condition was flat for both contexts, with approximately an equal amount of /g/ and /d/ responses following /al/, and actually more /d/ than /g/ responses following /ar/.

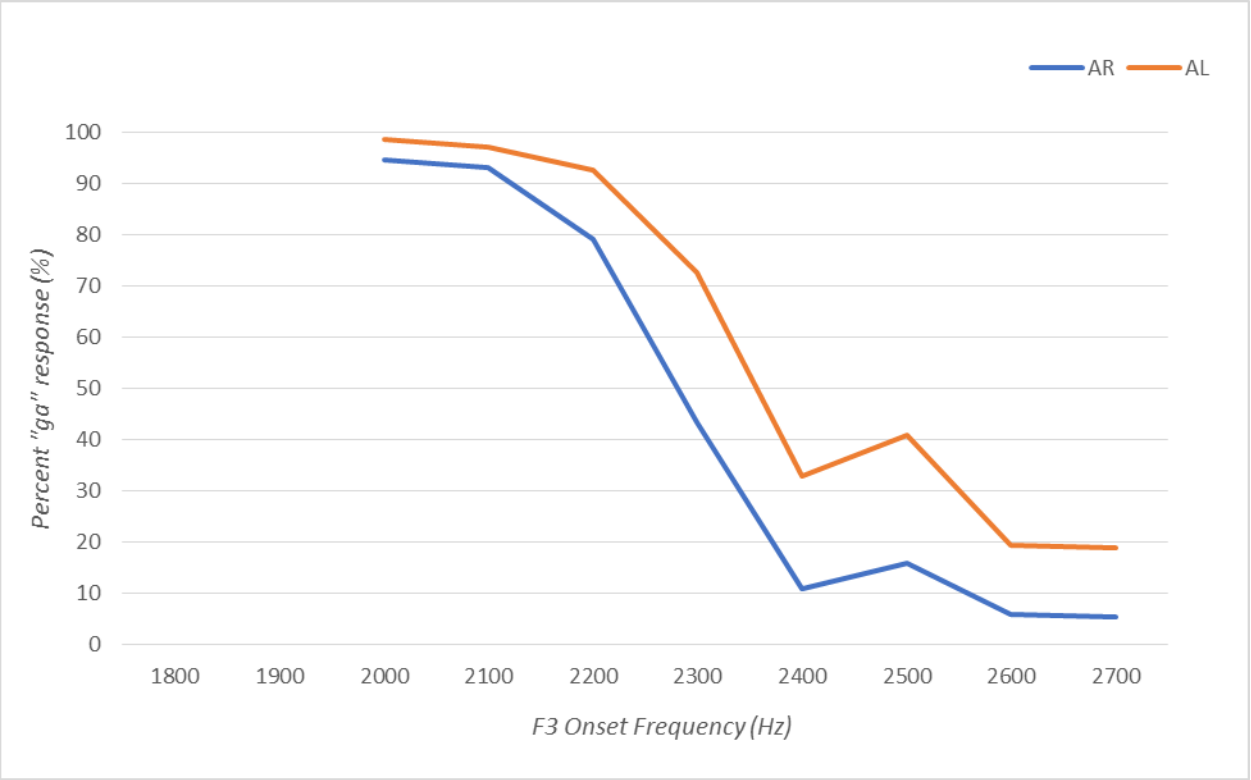

Figure 2. Average percent "*ga*" responses in the normal hearing condition

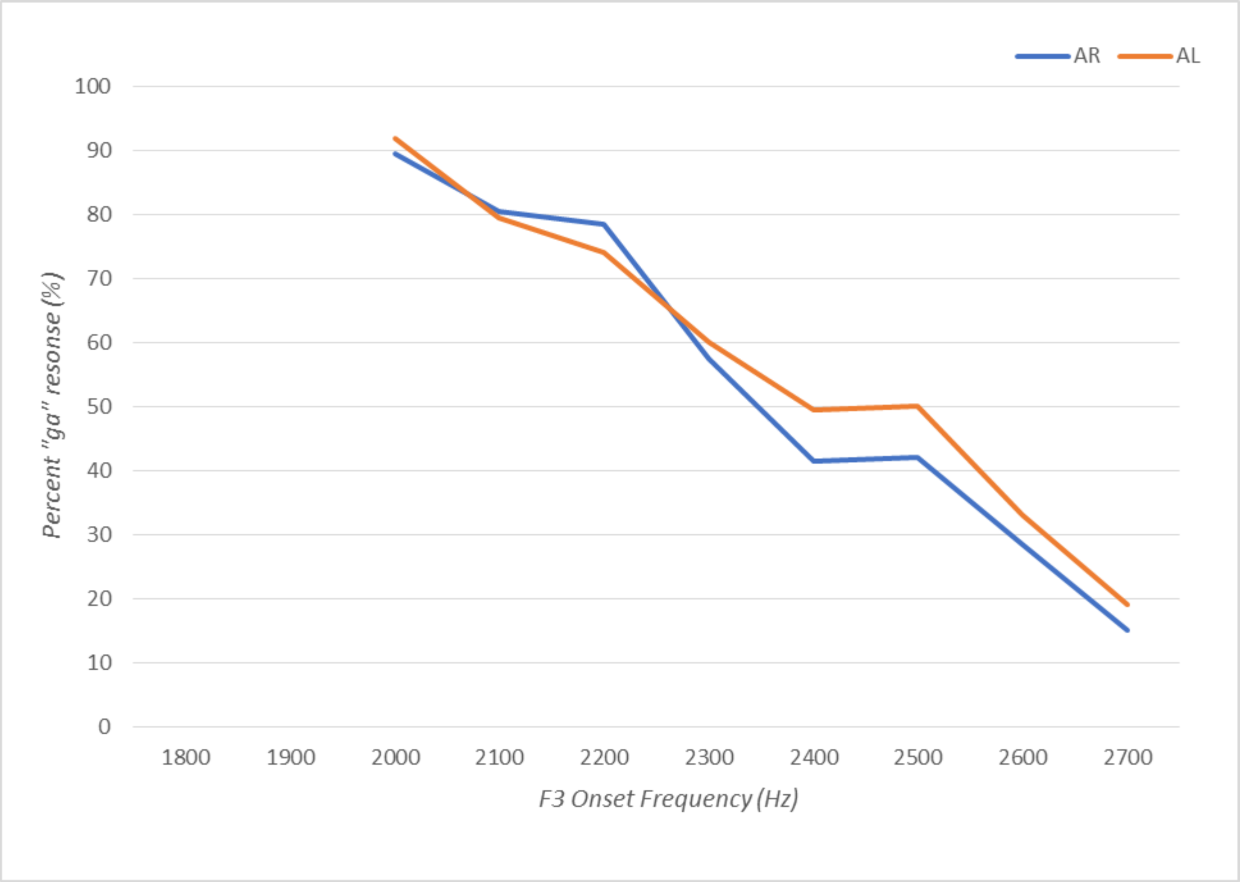

Figure 3. Average percent "ga" responses in the low-frequency hearing loss condition

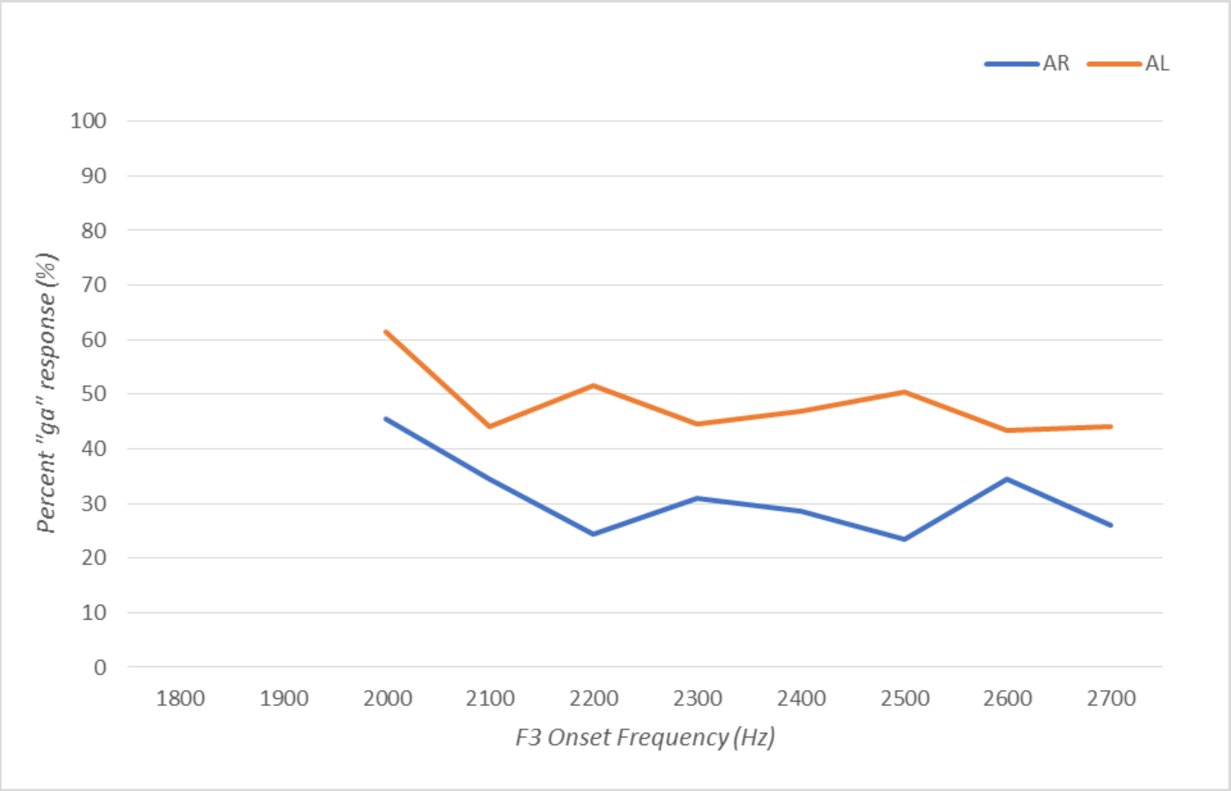

Figure 4. Average percent "*ga*" responses in the high-frequency hearing loss condition

The Poisson analysis across frequency bin and hearing loss condition was significantly different between the /ar/ and /al/ contexts overall, *Waid* $\chi2(1)=13.3$, $p< .01$. The average number of *ga* responses in the /ar/ condition was 19.1, and the average number of responses in the /al/ condition was 30.69. The *ga* count by frequency bin also was significant, *Waid* $\chi2(1)= 24.04$, $p<.01$, with an average count of 32.61 for the low-frequency bin and 17.24 in the high-frequency bin. However, the overall number of *ga* responses did not differ by hearing loss condition overall, *Waid* $\chi2(2)= 4.1$, $p=.129$. The average *ga* count was 25.09 for the normal hearing condition, 28.30 for the low-frequency hearing loss condition and 21.40 for the high-frequency hearing loss condition.

There was a significant interaction effect for frequency bin by hearing loss condition, *Waid* χ2(2)=8.04, *p*=.018. More specifically, under the high-frequency hearing loss condition the number of *ga* responses in the high-frequency bin was different than in the normal hearing condition, *Waid* χ2(1)=4.4, *p*=.2035. The average count for high-frequency hearing loss condition in the high-frequency bin was 19.05, but 12.00 for the normal hearing condition. This means that in the high-frequency hearing loss condition, the high-frequency bin (which typically is associated with *da* responses) was associated with a heightened number of *ga* responses.

Table 2. Average "*ga*" response counts by context, frequency bin and hearing loss condition

Context	Frequency Bin	Hearing Loss Condition		
		Normal	Low-frequency	High-frequency
/al/	Low-frequency	48.20	44.10	30.55
	High-frequency	16.85	21.15	23.25
/ar/	Low-frequency	27.50	28.35	16.95
	High-frequency	07.80	19.55	14.85

6.0 DISCUSSION

As expected, there was an observable boundary shift between the /ar/ and /al/ phonetic contexts in the normal hearing condition, but not in the low-frequency and high-frequency hearing loss conditions. The results of this study supported the hypothesis that a typical moderate high-frequency hearing loss would impede the phonetic context effect of /al/ and /ar/ on the perception of the /da/-/ga/ acoustic continuum. Moreover, the simulated hearing loss obliterated accurate perception of the syllables, which was somewhat surprising given that only a moderate loss was used and that some cues should have been available to the participants up to 2000 and possibly 3000 Hz. The mirror-image low-frequency hearing loss also adversely impacted about half of the participants. In 10 of the 20 participants, there was a perceptual boundary for the /ar/ and /al/ contexts, and in 9 of those 10 participants the boundary in the /al/ context shifted higher in frequency, resulting in more *ga* than *da* responses. These mixed results for the low-frequency loss suggested that about half of the participants were able to use the intact high-frequency cues, despite the overall drop in signal intensity. The remaining listeners may have needed a greater signal intensity or a more complete speech signal to process the higher frequencies cues. The implication of these results is that hearing loss likely prevents the use of spectral contrast and other coarticulatory information to anticipate and correct misperceptions, making listening more effortful by requiring more attention than would be required by normal hearing listeners.

This study had some limitations. The low-frequency hearing loss that was simulated was not typical of most low-frequency hearing losses, but rather a mirror image of the high-frequency hearing loss. Also, no participants with actual hearing losses were included. Although the simulation software produces expected results, some characteristics of hearing loss are likely missing from the simulations. The results also should be interpreted cautiously because the participants had normal hearing and no previous experience with hearing loss or a chance to adapt to the loss configurations used in the study. Using a fully randomized testing approach also may have increased the difficulty in the hearing loss conditions. In future studies, people with actual hearing losses should be used to verify results as their perceptual processes may differ from those of normal hearing people, by presenting the unmodified disyllables stimuli. For example, Aravamudhan and Lotto (2005) found no spectral context effect with cochlear implant users (although they were sensitive to temporal context) but later observed that spectral contrast was used by normal hearing participants when they listened to cochlear-implant-processed signals (Aravamudhan & Lotto, 2007). Finally, a stimulus construction error prevented examination of the full F3 frequency range, although given the shape of the identification functions it likely did not alter the results.

The results from this study do not provide direct information about the basic nature of speech perception, but if speech perception relies on access to gestures, it appears that access to speech gestures is fragile because even a moderate high-frequency hearing loss is sufficient to compromise perception of the gestures. Some participants had difficulty even when the critical speech acoustic information was present but at a low overall intensity level. It is likely that the low-frequency loss interfered with the relative spectral relationships of the stimuli for some of the listeners.

APPENDIX

EXAMPLES OF NORMAL AND SIMULATED HEARING LOSS FOR THE /al/ CONTEXT

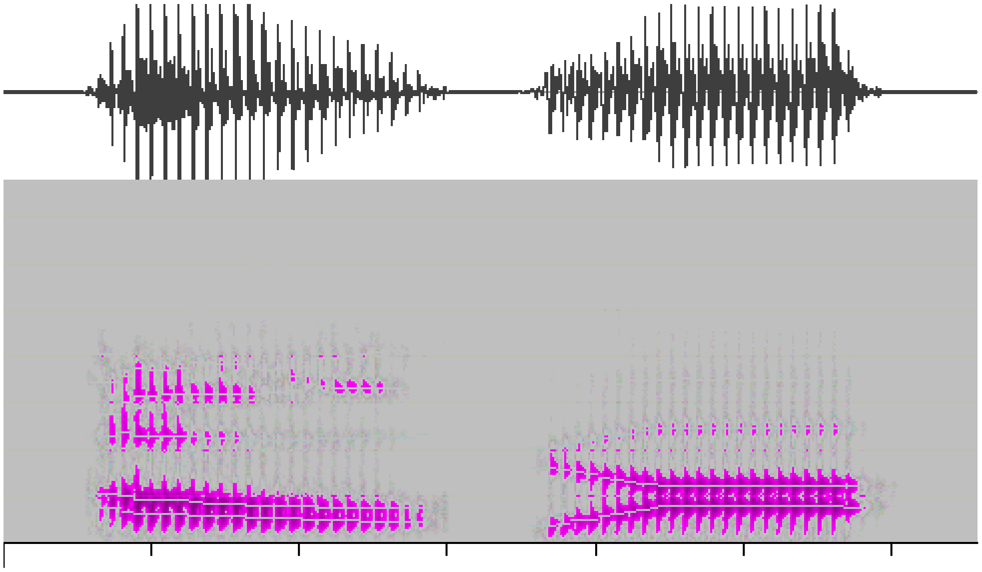

Figure 5. /al/ - 2000 Hz, Normal Hearing

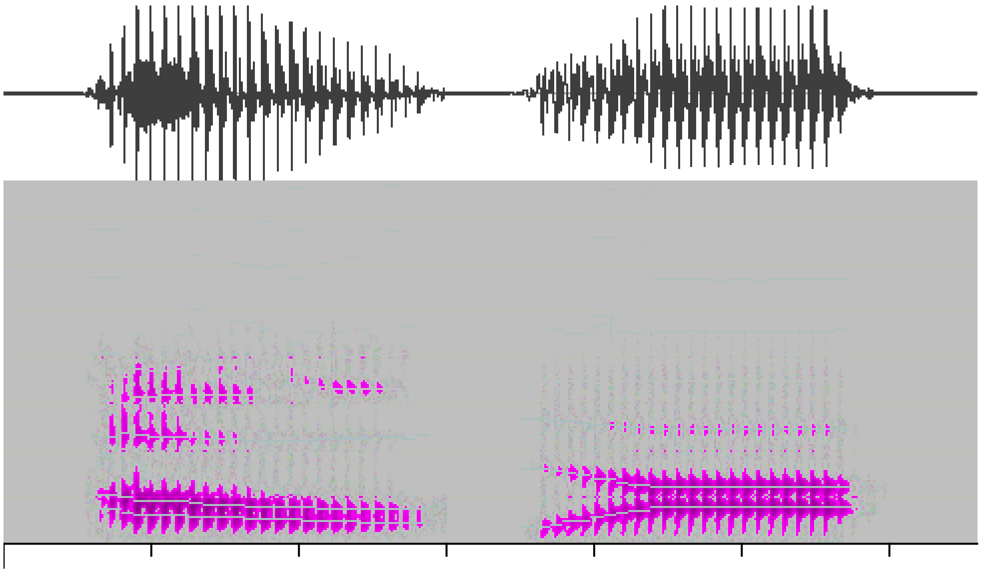

Figure 6. /al/ - 2700 Hz, Normal Hearing

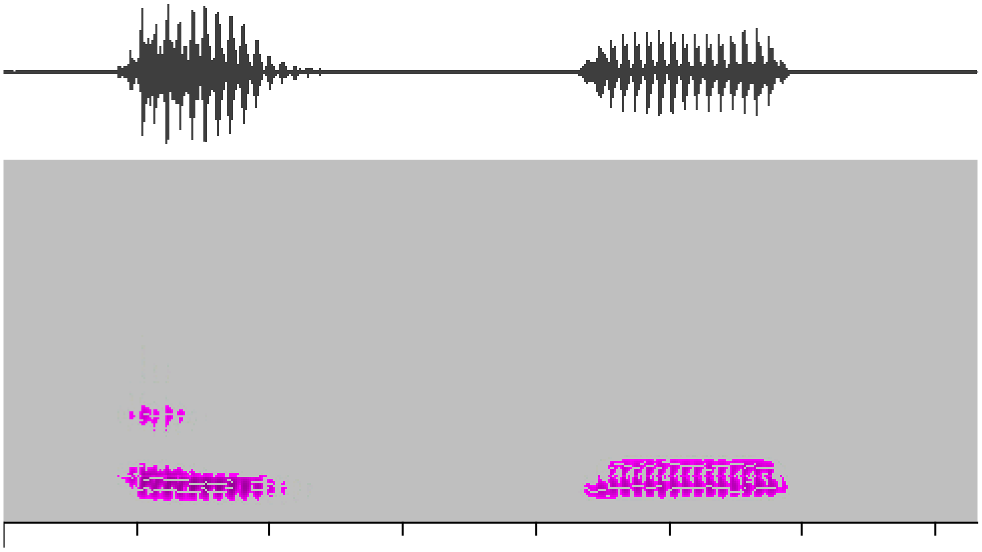

Figure 7. /al/ - 2000 Hz, Low-frequency Hearing Loss

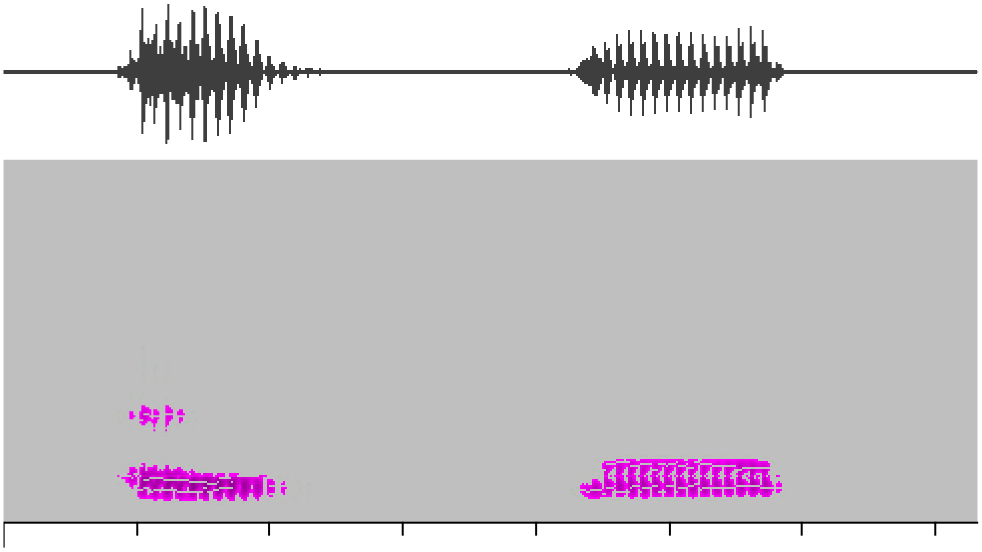

Figure 8. /al/ - 2700 Hz, Low-frequency Hearing Loss

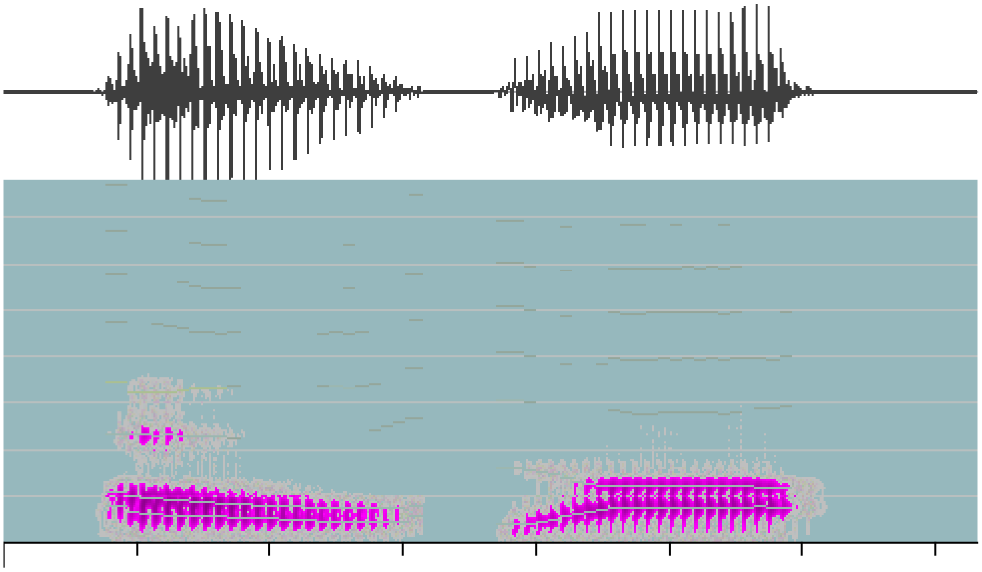

Figure 9. /al/ - 2000 Hz, High-frequency Hearing Loss

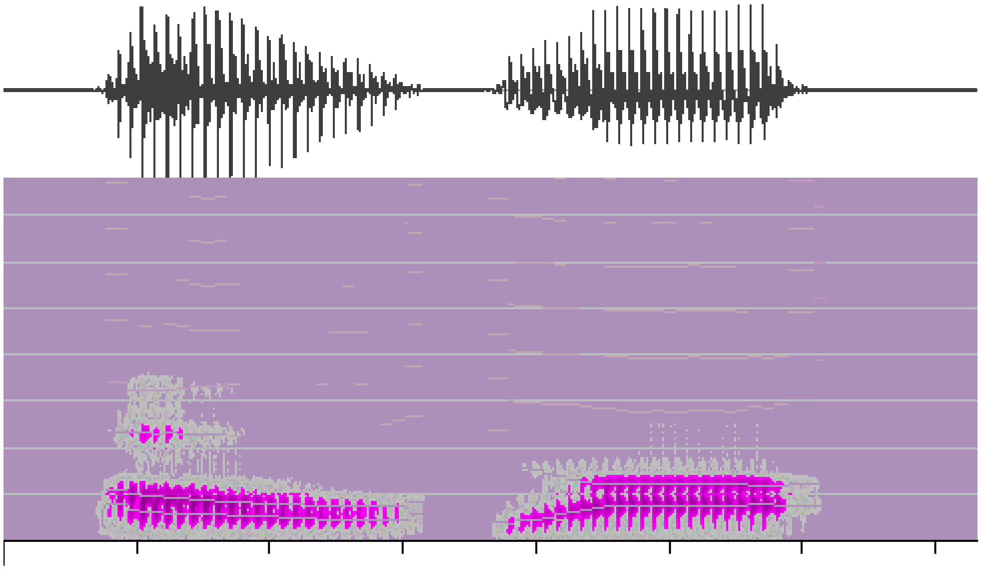

Figure 10. /al/ - 2700 Hz, High-frequency Hearing Loss

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