Original Article

Vowel Perception in Listeners With Normal Hearing and in Listeners With Hearing Loss: A Preliminary Study

Mark Hedrick · Lauren Charles · Nicole Drakopoulos Street

Department of Audiology & Speech Pathology, The University of Tennessee Health Science Center, Knoxville, TN, USA

Objectives. To determine the influence of hearing loss on perception of vowel slices.

Methods. Fourteen listeners aged 20–27 participated; ten (6 males) had hearing within normal limits and four (3 males) had moderate-severe sensorineural hearing loss (SNHL). Stimuli were six naturally-produced words consisting of the vowels /i a u æ ɛ ʌ/ in a /b V b/ context. Each word was presented as a whole and in eight slices: the initial transition, one half and one fourth of initial transition, full central vowel, one-half central vowel, ending transition, one half and one fourth of ending transition. Each of the 54 stimuli was presented 10 times at 70 dB SPL (sound press level); listeners were asked to identify the word. Stimuli were shaped using signal processing software for the listeners with SNHL to mimic gain provided by an appropriately-fitting hearing aid.

Results. Listeners with SNHL had a steeper rate of decreasing vowel identification with decreasing slice duration as compared to listeners with normal hearing, and the listeners with SNHL showed different patterns of vowel identification across vowels when compared to listeners with normal hearing.

Conclusion. Abnormal temporal integration is likely affecting vowel identification for listeners with SNHL, which in turn affects vowel internal representation at different levels of the auditory system.

Keywords. *Hearing Loss; Sensorineura; Speech Perception; Phonetics*

INTRODUCTION

Initial vowel perception theories suggested that listeners distinguish one vowel from another by comparing idealized steady-state target formant frequency values of the vowels [1]. Later work showed that this representation of vowel perception was inadequate, and could not explain how listeners accurately identify a vowel despite coarticulatory or surrounding phonetic influences, or despite the fact that the vowel may not have formants equaling the idealized target values [2,3]. Subsequent studies showed that presenting listeners segments of the vowel (e.g., transitions, or only the vowel centers) allowed nearly as accurate identification as when the entire syllable is presented [4]. Thus, all aspects of the vowel in a syllable—including formant values, formant trajectories throughout the vowel, duration, and phonetic context—all play a role in accurate vowel identification. In addition, all the vowel segments must be in the proper order; if not, vowel identification is decreased [5].

Studies that have examined vowel perception in listeners with sensorineural hearing loss (SNHL) have found that vowel misidentifications are usually caused by confusions of vowels having similar formant frequency values [6,7]. These misidentifications are magnified by reduced contrast in internal representations of vowels caused by reduced frequency selectivity in lis-

teners with SNHL [8].

Vowel perception is crucial for accurate word and sentence recognition, and thus is an important to investigate in listeners with hearing loss [9]. Few studies, however, have examined temporal manipulations or coding with reference to vowel perception by listeners with SNHL. Those studies that have often have used concurrent vowel paradigms in an attempt to mimic situations involving more than one speaker. Results from these studies show worse identification for listeners with SNHL than listeners with normal hearing (NH), owing to reduced spectro-temporal processing [10]. Because vowel perception is likely dependent on several segments of a vowel occurring over time for a single vowel, however, there is a need to study how temporal manipulations may affect single vowel perception in listeners with hearing loss without the compounding effects of the concurrent vowel paradigm.

Listeners likely perceive vowels based on an overall perception of several segments of a vowel changing over time. For a vowel in a consonant-vowel-consonant (CVC) syllable, these segments include the formant transitions to and from the vowel center. Formants and formant transitions are parts of the temporal fine structure of speech [11]; loss of tonotopicity and reduced across-fiber temporal coding would seem to preclude accurate internal representation of a formant transition [12,13]. One way to initially examine the effects of frequency and temporal coding in listeners with SNHL is to segment vowels in a CVC syllable into vowel centers (little formant frequency value change) and into initial and final formant transition segments (fluid formant frequency value change). For listeners with SNHL, it may be that spectro-temporal coding for even single vowels is problematic and may more completely describe perceptual deficits than focusing on frequency selectivity alone.

The purpose of the current study was to determine the influence of hearing loss on perception of vowel slices from naturally-produced /b V b/ syllables. The slices would be taken from the vowel center of the syllable, from the transition from the initial /b/ consonant to the vowel (initial transition), and from the transition from the vowel to the final consonant (final transition). Because of the perceptual and linguistic importance of vowel duration, there were slices of varying duration taken from the vowel center and the transitions. Our aims in this preliminary study were to determine whether listeners with SNHL would show an abnormal pattern of decreasing identification accuracy with decreasing slice duration as compared to listeners with NH, and whether there would be different patterns of identification across the listener groups for given vowels.

MATERIALS AND METHODS

Subjects
A total of 14 participants within the age range of 20–27 participated in this study. All participants were paid upon completion of the experiment. All listeners had at least an eighth-grade education, were native speakers of English, and able to use a computer mouse to label the vowel sounds they heard while wearing headphones. There were ten listeners (6 males; mean age, 21 years) with NH. These participants had hearing sensitivity less than or equal to 25 dB HL in the right ear [14]. They were recruited from the Department of Audiology & Speech Pathology, the university campus, and from local churches and community organizations. There were four listeners (3 males; mean age, 23 years) with SNHL. Participants met the qualifications of a mild-severe loss of 30–80 dB HL in the 250–4,000 Hz frequency range and provided a recent audiogram within the past year. Listeners with SNHL all had longstanding hearing losses and were recruited from the University Audiology Hearing Clinic. Table 1 presents demographic and audiometric information concerning the four listeners with SNHL. All potential listeners filled out a case history form, and those individuals with cognitive, neurological, or learning deficits were excluded.

All participants provided written informed consent and were given a free hearing screening. This study was approved by Institutional Review Board # IORG0000051.

Stimuli
The stimuli consisted of six consonant-vowel-consonant (CVC) syllables spoken by a middle-aged adult male. Six vowels were used /i a u æ ɛ ʌ/ in a /b V b/ context, making the words 'beeb,' 'bob,' 'boob,' 'bab,' 'beb,' and 'bub.' Five different productions of each syllable were generated by the speaker, and the middle production was used as the experimental stimulus. Stimuli were recorded in a quiet room using a quality microphone (Spher-O-Dyne) held approximately 1 cm from the speaker's mouth. The microphone output was fed to a preamplifier (Model MA2, Tucker-Davis Technologies, Alachua, FL, USA) and routed to a 16-bit A/D converter (Model DD1, Tucker-Davis Technologies) and sampled at a 12.5 kHz rate. The recordings were edited into individual tokens using a waveform manipulation software package (Adobe Audition ver. 1.5, Adobe Systems Inc., San Jose, CA, USA). A waveform editor in this software package was used to slice the individual syllables into eight approximate segments: the beginning transition, one half of the beginning transition, one fourth of the beginning transition, full central steady-state vowel,

Table 1. Information about listeners with sensorineural hearing loss, including audiometric pure-tone air-conduction thresholds in dB HL for the right (test) ear

Listener	Age (year)	Hearing aids	Etiology	Frequency (kHz)			
				0.5	1	2	4
HI 1	23	Yes	Unknown	45	65	70	65
HI 2	21	Yes	Unknown	55	65	70	90
HI 3	22	Yes	Unknown	60	75	70	70
HI 4	27	Yes	Unknown	25	60	70	95

HI, listeners with hearing loss.

one half of the central vowel, ending transition, half of ending transition, and one fourth of ending transition. This made a total of 54 stimuli. For the half vowel centers, the midpoint of the vowel center was selected, and then a quarter of the total vowel center duration was then selected on either side of the midpoint. Spectrographically, an initial transition was defined as the beginning changes in formant frequency from the burst to the vowel steady-state; similarly, a final transition was defined as the beginning change in formant frequency from the vowel steady-state to cessation of periodicity at final stop closure. For initial transition durations, the half transition comprised the beginning of the syllable to the transition midpoint; the quarter transition comprised the first quarter of the transition starting at the beginning of the syllable. Likewise, for final transition durations, the half transition comprised the midpoint of the transition to the end of periodicity; the quarter transition comprised the segment at the end of periodicity. All waveform cuts were made at zero crossings to present acoustic distortions; this also resulted in the above segments being approximate one-half and one-fourth durations. Selection of where to cut the transitions was based upon initial and final formant movement as seen in spectrographic representations of the stimuli (Fig. 1).

Procedure

Listeners were tested individually in a sound-attenuated room. Stimuli were output by a Tucker-Davis DD1 D/A converter, low-pass filtered at 4.9 kHz (PF1, Tucker-Davis Technologies), routed to a headphone buffer (HB, Tucker-Davis Technologies), and then sent to Sennheiser HD265 headphones inside an Industrial Acoustics Company (Winchester, UK) sound booth. Stimuli were presented via the headphones into the right ear of the participants; the stimuli were presented in 10 random orders for a
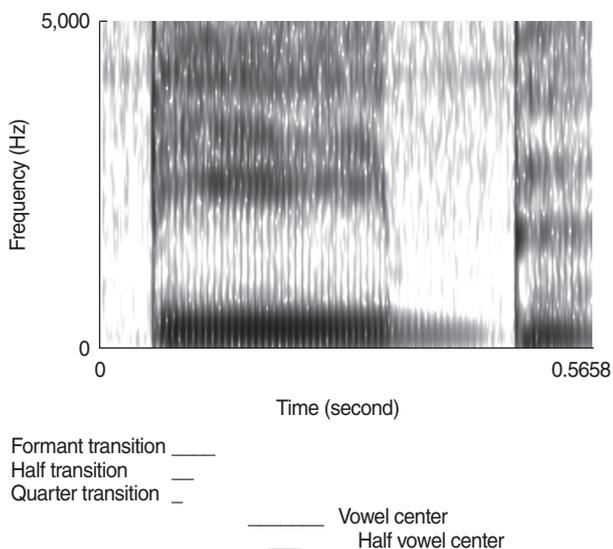
total of 540 presentations. Stimuli were presented at 70 dB SPL (sound press level) for all listeners. For the listeners with SNHL, all stimuli were shaped to mimic the gains of an appropriately-fit hearing aid. First, the audiometric thresholds from the right ear of a listener with SNHL were logged into a Veri-Fit system. Target gain by audiometric frequency was then selected using the NAL-NL1 formula. These target gain values were then used to develop a software gain function (using Adobe Audition ver. 1.5) for the given listener; this gain function was then applied to all 54 stimuli. In this way, each of the listeners with hearing loss received listener-specific stimuli. All listeners used a computer mouse to select the corresponding word on the screen.

To verify the stimuli were at a comfortable listening level and familiarity with the stimuli, participants were given three practice runs using the six whole syllables and were asked to identify the word they heard by using the computer mouse to select the corresponding word on the computer screen. On each trial run, listeners were given correct-answer feedback by a green flash on the computer screen. A red flash indicated the response was incorrect. All listeners correctly identified the whole syllables.

RESULTS

For analysis of listener responses, portions of the stimuli were grouped according to initial transition slices, final transition slices, and whole syllable/vowel center slices.

Fig. 1. A spectrogram of the whole syllable "beeb," illustrating the slices for vowel centers and transitions.

Formant transition ____
Half transition   __
Quarter transition _
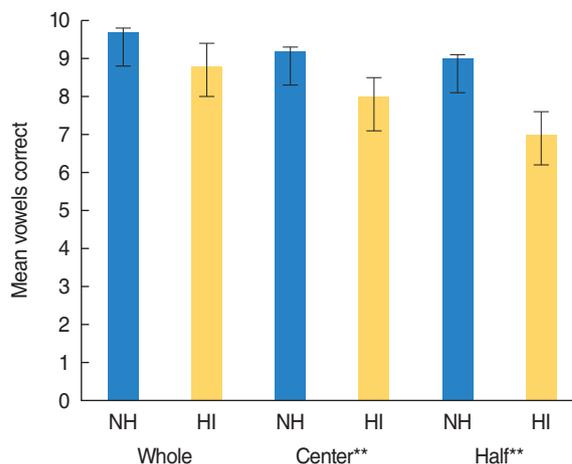
_____ Vowel center
____ Half vowel center

Fig. 2. Mean number correct vowel identifications for whole syllable, vowel center and half vowel center slices. In this and succeeding figures, Results show that HI listeners do as well as NH listeners in identifying the vowel when the whole syllable is presented. But, when only the steady-state or center of the vowel, or only half the center part of the vowel, is present, the HI listeners are significantly poorer in identifying the vowel correctly compared to the NH listeners. Error bars represent standard error of the mean. Asterisks indicate significant differences between NH and HI listeners for the vowel centers and half vowel centers (**$P<0.01$). NH, listeners with normal hearing; HI, listeners with hearing loss.

Whole syllable, vowel steady-state center and half of vowel center

Fig. 2 shows the mean identification results for the whole syllable, the vowel center slice only, and half of the vowel center slice when collapsed across the six vowels. A repeated-measures two-way analysis of variance (ANOVA) was computed on the data shown in Fig. 2 using slice or duration (whole syllable, vowel center, half vowel center) as the within-subject variable, group classification (NH or hearing loss) as the between-subject variable, and mean number correct identification as the dependent variable. To guard against violations of sphericity, Huynh-Feldt corrections were used in this and succeeding analyses, as were computations of partial η^2 to determine effect size. The results from the ANOVA revealed a significant main effect for duration ([1.762, 21.140], $F=30.847$, $P<0.001$, $\eta^2=0.720$), a main effect for group ([1, 12], $F=14.053$, $P=0.003$, $\eta^2=0.539$), and a significant duration × group interaction ([1.762, 21.140], $F=9.828$, $P=0.001$, $\eta^2=0.450$). To explore the duration×group interaction, *post hoc* pairwise comparisons were computed and showed a significant difference between groups for the vowel centers ($P=0.004$) and for half vowel centers ($P=0.002$), using an alpha level of 0.01.

To determine whether vowel identity influenced identification patterns, a three-way ANOVA was computed, this time adding vowel identity as an additional within-subject factor. These results showed a significant main effect for vowel ([2.778, 33.322], $F=5.701$, $P=0.004$, $\eta^2=0.322$), a significant main effect of duration ([1.759, 21.107] $F=30.988$, $P<0.001$, $\eta^2=0.721$), and a significant main effect of group ([1, 12], $F=14.088$, $P=0.003$, $\eta^2=0.540$). Significant interactions included a significant vowel x group interaction ([2.778, 33.332], $F=34.425$, $P=0.041$, $\eta^2=0.207$), a significant duration×group interaction ([1.759, 21.107], $F=9.838$, $P=0.001$, $\eta^2=0.450$), a significant vowel× duration interaction ([6.844, 82.126], $F=3.649$, $P=0.002$, $\eta^2=0.233$), and a significant vowel×duration×group interaction ([6.844, 82.126], $F=5.117$, $P<0.001$, $\eta^2=0.299$). The three-way interaction between vowel, slice, and listener group shows that there are different response patterns for different slice durations of different vowels depending on the listener group. Listeners with NH performed consistently across all stimuli except for the vowel /æ/, for which performance on average became worse for each shortening of the stimulus and approximating that of listeners with hearing loss for the half center duration. The listeners with SNHL, however, performed worse than that of listeners with NH for several conditions.

In particular, these listeners' performance fell below 85% for all three stimuli (whole syllable, vowel center, half center) containing /æ/ and /ʌ/, and for half center stimuli for the vowels /u/ and /a/. What is surprising is that the listeners with hearing loss had correctly identified the whole syllables before the experimental data was collected, yet their identification for whole syllables containing /æ/ and /ʌ/ was lower than expected in the ex-

perimental data. These patterns taken together show why a three-way interaction occurred—there are different response patterns for different durations of different vowels depending on the listener group.

Finally, to determine whether the decrease in performance by the listeners with hearing loss was greater than that experienced by the listeners with NH, differences were computed for each listener as the vowel slices became shorter. That is, the difference in identification performance was computed between the whole syllable versus the vowel center, between the vowel center and the half vowel center, and between the whole syllable and the half vowel center. The mean differences were then used as the dependent variable in a three-way repeated-measures ANOVA using vowel identity, slice or duration, and group as the factors. The results of this ANOVA showed a significant main effect of vowel ([4.912, 58.945] $F=4.701$, $P=0.001$, $\eta^2=0.281$), a significant main effect of duration ([1.373, 16.480], $F=7.844$, $P=0.008$, $\eta^2=0.395$), and a significant main effect of group ([1, 12], $F=15.614$, $P=0.002$, $\eta^2=0.565$). Significant interactions included a significant vowel x group interaction ([4.912, 58.945], $F=6.709$, $P<0.001$, $\eta^2=0.359$), and a significant vowel×duration x group interaction ([4.431, 53.167], $F=2.790$, $P=0.031$, $\eta^2=0.189$). To help explore the significant three-way interaction, *post hoc* pairwise comparisons were performed, and showed a significant difference between groups for the difference from whole syllable to half center ($P=0.002$), at an alpha level of 0.01. This rate of change difference suggests a difference in temporal integration of information between 315 ms (effective mean duration of the whole vowels in the syllables) and 77 ms (mean duration of the half vowel centers).
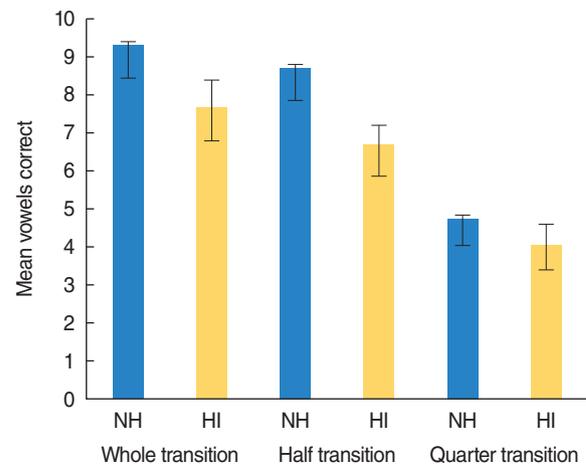

Fig. 3. Mean number correct vowel identifications for initial transition, half and quarter initial transition. Although there was a statistically significant overall difference between groups, none of the group comparisons for whole transition, half transition, or quarter transition reached statistical significance. Error bars represent standard error of the mean. NH, listeners with normal hearing; HI, listeners with hearing loss.

Initial transitions

Fig. 3 shows the mean identification results for the initial transition, the beginning half of the initial transition, and the beginning quarter of the initial transition collapsed across vowels. A two-way ANOVA was computed and the results showed a significant main effect for slice or duration ([1.632, 19.582], $F=$ 159.003, $P<0.001$, $\eta^2 =0.930$), and a significant main effect for group ([1, 12], $F=9.273$, $P=0.010$, $\eta^2 =0.436$).

To determine whether vowel identity influenced identification patterns, a three-way ANOVA was computed, this time adding vowel identity as an additional within-subject factor. These results showed a significant main effect for vowel ([2.538, 30.455], $F=13.711$, $P<0.001$, $\eta^2 =0.533$), a significant main effect for duration ([1.639, 19.670], $F=159.778$, $P<0.001$, $\eta^2 =0.930$), and a significant main effect of group ([1, 12], $F=9.251$, $P= 0.010$, $\eta^2 =0.435$). There was also a significant vowel×duration interaction ([10, 120], $F=5.408$, $P<0.001$, $\eta^2 =0.311$). Noteworthy is the significant vowel×duration interaction, and a significant main effect of listener group. The vowel×duration interaction may be explained by the fact that some vowels simply yielded better performance than the other vowels, even at quarter transition duration.

Finally, to determine whether the decrease in performance by the listeners with hearing loss was greater than that experienced by the listeners with NH, differences were computed for each listener as the transition slices became shorter. The results of this three-way ANOVA showed a significant main effect of vowel ([5, 60], $F=6.622$, $P<0.001$, $\eta^2 =0.356$), and a significant main effect of duration ([1.548, 18.579], $F=90.226$, $P<0.001$, $\eta^2 =0.883$).
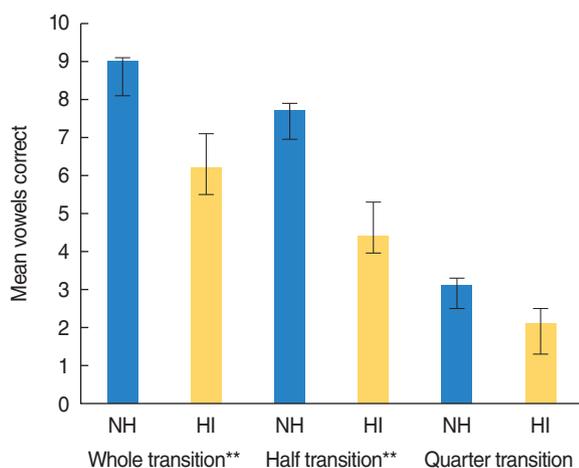

Fig. 4. Mean number correct vowel identifications for final transition, half and quarter final transition. Error bars represent standard error of the mean. Asterisks indicate significant differences between NH and HI for the whole transitions and half transitions (**$P<0.01$). That is, when only the end part of the syllable, or half of the ending part, is present, the HI listeners are significantly poorer at correctly identifying the syllable vowel than are the NH listeners. NH, listeners with normal hearing; HI, listeners with hearing loss.

There was also a significant duration×group interaction ([1.548, 18.579], $F=5.202$, $P=0.022$, $\eta^2 =0.302$), and a significant vowel×duration interaction ([5.959, 71.505], $F=4.183$, $P=0.001$, $\eta^2 =0.258$). While there was a significant slice duration ×group interaction, *post hoc* pairwise comparisons did not show significant differences between groups for different slice durations at the 0.01 alpha level.

Final transitions

Fig. 4 shows the mean identification results for the final transition, the ending half of the initial transition, and the ending quarter of the initial transition collapsed across vowels. A two-way ANOVA was computed and the results showed a significant main effect of slice duration ([2, 24], $F=149.188$, $P<0.001$, $\eta^2 =0.926$), and a significant main effect of group ([1, 12], $F=34.444$, $P< 0.001$, $\eta^2 =0.742$). There was also a significant duration×group interaction ([2, 24], $F=7.352$, $P=0.003$, $\eta^2 =0.380$). To explore the duration ×group interaction, *post hoc* pairwise comparisons were computed and showed a significant difference between groups for the whole final transition vowel centers ($P\leq0.001$) and for the half transition ($P<0.001$), using an alpha level of 0.01.

To determine whether vowel identity influenced identification patterns, a three-way ANOVA was computed, this time adding vowel identity as an additional within-subject factor. These results showed a significant main effect of vowel ([3.241, 38.889], $F=9.362$, $P<0.001$, $\eta^2 =0.438$), a significant main effect of duration ([1.691, 20.295], $F=162.470$, $P<0.001$, $\eta^2 =0.931$), and a significant main effect of group ([1, 12], $F=20.686$, $P=0.001$, $\eta^2 =0.633$). There was also a significant vowel×group interaction ([3.241, 38.889], $F=3.814$, $P=0.015$, $\eta^2 =0.241$), a significant duration×group interaction ([1.691, 20.295], $F=8.090$, $P=0.004$, $\eta^2 =0.403$), a significant vowel×duration interaction ([9.323, 111.880], $F=6.110$, $P<0.001$, $\eta^2 =0.337$), and a significant vowel×duration×group three-way interaction ([9.323, 111.880], $F=2.354$, $P=0.017$, $\eta^2 =0.164$). Noteworthy is again a significant vowel×duration×listener group interaction, meaning that there are different response patterns for different durations of different vowels depending on the listener group. The listeners with NH had identification performance below 85% for the vowel /æ/ for all final transition durations, for /ɛ/ and /ʌ/ for the half-transition stimuli, and for all vowels for the approximate quarter-transition stimuli. The listeners with hearing loss had identification performance below 85% for /i/, /æ/, /u/, and /ʌ/ for the whole final transitions, and for all vowels for the half- and quarter-transition slices. To explore the duration×group interaction, *post hoc* pairwise comparisons were computed and showed a significant difference between groups for the whole final transition ($P<0.001$) and for the half final transition ($P<0.001$), using an alpha level of 0.01.

Finally, to determine whether the decrease in performance by the listeners with hearing loss was greater than that experienced by the listeners with NH, differences were computed for each

listener as the transition slices became shorter. The results of this three-way ANOVA showed a significant main effect of vowel ($[5, 60]$, $F=6.939$, $P<0.001$, $\eta^2 =0.366$), and a significant main effect of duration ($[1.607, 19.281]$, $F=62.609$, $P<0.001$, $\eta^2 =0.839$).

There was also a significant vowel×group interaction ($[5, 60]$, $F=4.219$, $P=0.002$, $\eta^2 2=0.260$), a significant duration×group interaction ($[1.607, 19.281]$, $F=15.739$, $P<0.001$, $\eta^2 =0.567$), and a significant vowel×duration interaction ($[5.631, 67.573]$, $F=5.463$, $P<0.001$, $\eta^2 =0.313$). To explore the significant group ×duration interaction, *post hoc* pairwise comparisons were performed, and showed a significant difference between groups for the difference from half to quarter transition ($P=0.003$), at an alpha level of 0.01. This rate of change difference suggests a difference in temporal integration of information between 41 ms (mean duration of the half final transition) and 18 ms (mean duration of the quarter final transition).

DISCUSSION

Our aims were to determine whether listeners with SNHL would show an abnormal pattern of decreasing identification accuracy with decreasing slice duration as compared to listeners with NH, and whether there would be different patterns of identification across the listener groups for given vowels. Listeners were asked to identify vowels from slices of vowel centers, of initial transitions, and final transitions. The results showed that listeners with SNHL had a steeper rate of decreasing vowel identification with decreasing slice duration as compared to listeners with NH, and the listeners with hearing loss showed different patterns of vowel identification across vowels when compared to listeners with NH. These findings are further discussed below.

Whole syllable, vowel steady-state center and half of vowel center

Results from the current study for the whole syllables are in agreement with earlier studies in that the listeners with hearing loss appear to have vowel misidentifications arising from reduced contrast in internal representations of vowels via reduced frequency selectivity [8].

As expected, there were differences between listener groups as the stimuli were shortened from whole syllables to only vowel centers, and then only half of the vowel centers. The rate of performance decrement was significantly greater for the listeners with hearing loss going from the whole syllable to the half center slices. This time frame covered several hundred milliseconds. This result implies that the temporal sampling of the stimulus may be insufficient and/or distorted by the hearing loss. A potential mechanism for multiple looks in perceiving speech sounds would involve a comparison of a phoneme template stored in long-term memory with repetitive sampling of the incoming stimulus in short-term memory [15-17]. Degraded sampling of some form may then harm development of either representation in short-term or long-term memory. Results from the current study cannot allow for further speculation on the actual degradation caused by the hearing loss.

All the analyses including vowel identity as a factor showed vowel identity to be a significant factor. This suggests that bottom-up peripheral processing of vowels cannot completely explain the current results. That is, there were bias effects as some vowels were simply recognized better than others. There also were vowel×group interactions, showing that identification patterns were different between listeners with NH versus listeners with hearing loss. These results suggest that listeners with hearing loss may have vowel perceptual space demarcations different from that of listeners with NH [18]. Since all the listeners with hearing loss in the current study had hearing losses that were longstanding (and likely congenital), it is unlikely that these listeners had much if any significant time of NH or time in which vowel perceptual space was unaffected by the hearing loss. Across all stimuli, the cardinal vowels /i a u/ consistently yielded the better performance for the listeners with NH – but not always for the listeners with hearing loss. This is further evidence suggesting problematic vowel perceptual space in listeners with hearing loss.

Other reports have posited that peripheral representation may not be sufficient for explaining vowel identification, particularly for concurrent vowel identification [19-22]. It may be that hearing loss not only affects peripheral representation, but also more central representation of vowels. It is possible that some differences of performance by listeners with hearing loss across vowels in the current study arose from speaker idiosyncratic productions [23] – but, given the above results, a more general explanation may be altered vowel perceptual space or altered vowel templates.

Initial and final transitions

Results from the current study on transitional segments show that listeners with SNHL had, on average, difficulty with using transitions to identify vowels. Previous research has shown a similar difficulty by listeners with hearing loss in using transitions for identifying stop consonants [24]. If listeners likely perceive vowels based on an overall perception of several segments of a vowel changing over time, then loss of tonotopicity and reduced across-fiber temporal coding may be preventing accurate internal representation of a formant transition [12,13]. For both initial and final transition slices, significant group×duration interactions using mean differences or rate of change show that the listeners with hearing loss had performance decrements greater than that of listeners with NH. For the final transition slices, the significant decrement was between approximately 40 and 20 ms.

Even though this is a different time scale from that listed for the vowel center slices, it would still likely involve some tempo-

ral integration of information, even if the time scales may suggest different physiologic mechanisms of integration. For listeners with SNHL, it may be that spectro-temporal coding for even single vowels is problematic and may more completely describe perceptual deficits than focusing on frequency selectivity alone. For instance, in the current study, the relatively poor performance by the listeners with hearing loss on the whole syllable /æ/ and /ʌ/ stimuli in the experimental condition also coincided with relatively poor performance on using transition segments to accurately identify these vowels as well. For both listeners with SNHL and listeners with NH, the approximate quarter-duration transitions probably did not have enough frequency extent to enable correct identification exceeding 50% [25].

Results from the current study show that listeners with SNHL may have both peripheral coding and more central acoustic-phonetic mapping difficulties. It is difficult to say how exactly one might influence the other, or how they may work synergistically to adversely affect speech perception. Future studies using models of speech that include both bottom-up and top-down processes may prove useful in gaining a more complete picture of auditory processing. Such models include the distributed cohort model, having a neural network influenced by both processes [26], and the TRACE model, in which top-down processing affects bottom-up processing [27].

There are limitations to the current preliminary study—small listener sample size, a stimulus set generated from only one speaker, and not all vowels of English represented.

Regarding the small sample size, however, it must also be stated that statistically significant group factor results are evidence of sufficient statistical power; having a larger sample size would not make the results more significant. Furthermore, the large effect sizes for group accompanying the statistically significant analyses suggest that the results would likely be similar for similar subjects even with a larger sample size. The occurrence of numerous higher-order statistical interactions with such a small sample size would again suggest that the results would be similar with similar subjects even with a larger sample size. A strength of the current study is having listeners of similar ages (20s) in both groups, thus controlling for age-related effects. Thus, this preliminary study into vowel perception by listeners with SNHL shows that subsequent studies may provide much more understanding of how SNHL affects speech perception.

In conclusion, our aims were to determine whether listeners with SNHL would show an abnormal pattern of decreasing identification accuracy with decreasing slice duration as compared to listeners with NH, and whether given vowels would be more difficult to identify than others. Listeners with hearing loss did show that listeners with SNHL had a steeper rate of decreasing vowel identification with decreasing slice duration as compared to listeners with NH, suggesting abnormal temporal integration in the listeners with hearing loss. Listeners with hearing loss showed different patterns of vowel identification across

vowels when compared to listeners with NH, indicating vowel perceptual demarcation different from that of listeners with NH. Further research may show how these two effects may interact one with another to influence the vowel perception of listeners with SNHL.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

REFERENCES

1. Peterson GE, Barney HL. Control methods used in a study of vowels. J Acoust Soc Am. 1952 Mar;24(2):175-84.
2. Ohde RN, German SR. Formant onsets and formant transitions as developmental cues to vowel perception. J Acoust Soc Am. 2011 Sep;130(3):1628-42.
3. Strange W. Evolving theories of vowel perception. J Acoust Soc Am. 1989 May;85(5):2081-7.
4. Strange W, Jenkins JJ, Johnson TL. Dynamic specification of coarticulated vowels. J Acoust Soc Am. 1983 Sep;74(3):695-705.
5. Kuwabara H. An approach to normalization of coarticulation effects for vowels in connected speech. J Acoust Soc Am. 1985 Feb;77(2):686-94.
6. Molis MR, Leek MR. Vowel identification by listeners with hearing impairment in response to variation in formant frequencies. J Speech Lang Hear Res. 2011 Aug;54(4):1211-23.
7. Richie C, Kewley-Port D, Coughlin M. Discrimination and identification of vowels by young, hearing-impaired adults. J Acoust Soc Am. 2003 Nov;114(5):2923-33.
8. Bacon SP, Brandt JF. Auditory processing of vowels by normal-hearing and hearing-impaired listeners. J Speech Hear Res. 1982 Sep;25(3):339-47.
9. Kewley-Port D, Burkle TZ, Lee JH. Contribution of consonant versus vowel information to sentence intelligibility for young normal-hearing and elderly hearing-impaired listeners. J Acoust Soc Am. 2007 Oct;122(4):2365-75.
10. Arehart KH, Rossi-Katz J, Swensson-Prutsman J. Double-vowel perception in listeners with cochlear hearing loss: differences in fundamental frequency, ear of presentation, and relative amplitude. J Speech Lang Hear Res. 2005 Feb;48(1):236-52.
11. Rosen S. Temporal information in speech: acoustic, auditory and linguistic aspects. Philos Trans R Soc Lond B Biol Sci. 1992 Jun;336(1278):367-73.
12. Bidelman GM, Heinz MG. Auditory-nerve responses predict pitch attributes related to musical consonance-dissonance for normal and impaired hearing. J Acoust Soc Am. 2011 Sep;130(3):1488-502.
13. Swaminathan J, Heinz MG. Predicted effects of sensorineural hearing loss on across-fiber envelope coding in the auditory nerve. J Acoust Soc Am. 2011 Jun;129(6):4001-13.
14. American National Standards Institute. Specification for audiometers (S3.6-2010). New York: American National Standards Institute; 2010.
15. Viemeister NF, Wakefield GH. Temporal integration and multiple looks. J Acoust Soc Am. 1991 Aug;90(2 Pt 1):858-65.
16. Holt RF, Carney AE. Multiple looks in speech sound discrimination in adults. J Speech Lang Hear Res. 2005 Aug;48(4):922-43.

17. Moore BC. Temporal integration and context effects in hearing. J Phon. 2003 Jul-Oct;31(3-4):563-74.

18. McCaffrey HA, Sussman HM. An investigation of vowel organization in speakers with severe and profound hearing loss. J Speech Hear Res. 1994 Aug;37(4):938-51.

19. Alain C, Reinke K, He Y, Wang C, Lobaugh N. Hearing two things at once: neurophysiological indices of speech segregation and identification. J Cogn Neurosci. 2005 May;17(5):811-8.

20. Griffiths TD, Warren JD. The planum temporale as a computational hub. Trends Neurosci. 2002 Jul;25(7):348-53.

21. McKeown JD. Perception of concurrent vowels: the effect of varying their relative level. Speech Commun. 1992 Mar;11(1):1-13.

22. Warren JD, Jennings AR, Griffiths TD. Analysis of the spectral envelope of sounds by the human brain. Neuroimage. 2005 Feb;24(4):1052-7.

23. Nabelek AK, Czyzewski Z, Krishnan LA. The influence of talker differences on vowel identification by normal-hearing and hearing-impaired listeners. J Acoust Soc Am. 1992 Sep;92(3):1228-46.

24. Hedrick MS, Schulte L, Jesteadt W. Effect of relative and overall amplitude on perception of voiceless stop consonants by listeners with normal and impaired hearing. J Acoust Soc Am. 1995 Sep;98(3):1292-303.

25. Kewley-Port D, Goodman SS. Thresholds for second formant transitions in front vowels. J Acoust Soc Am. 2005 Nov;118(5):3252-60.

26. Gaskell MG, Marslen-Wilson WD. Integrating form and meaning: a distributed model of speech perception. Lang Cogn Process. 1997; 12(5/6):613-56.

27. McClelland JL, Elman JL. The TRACE model of speech perception. Cogn Psychol. 1986 Jan;18(1):1-86.