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Speech-cue enhancement for the hearing impaired: Amplification of burst/murmur cues for improved perception of final stop voicing*

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Abstract—A further study is reported from a program of research exploring the improvement of speech perception by hearing-impaired persons via enhancement of acoustic features of consonants (10,11). Enhancements were applied to certain acoustic segments of consonants, segments known to be useful in consonant perception by normal-hearing persons but often not for persons with severe/profound hearing losses. The consonants were /k/, /t/, /g/, and /d/ located as the final phoneme in /bæC/ words; the voicing feature difference of /k/ versus /g/ and /t/ versus /d/ was the focus of study. The results showed that stop voicing perception improved to at least 90 percent for 3/4 of the listeners when the voiced murmur segments during /d/ and /g/ and the release bursts of /t/ and /k/ were amplified above their natural levels. The audibility of the enhanced segments generally explained differences between the listeners who showed large versus minimal improvements. One training session for stop voicing perception with the cue-enhanced words seemed sufficient to effect maximum performance improvement.

INTRODUCTION

Future generations of digital hearing aids may have the capability to enhance or exaggerate acoustic segments in speech that are otherwise indiscriminable for hearing-impaired persons with deficient speech perception. The speech acoustic segments to be enhanced by these aids should contain the cues of importance for distinguishing consonants in speech (8). For example, some speech acoustic cues that can be used to differentiate the final consonants in BAT versus BAD are the presence of a low-pitched murmur immediately preceding the release of /d/ but not of /t/, and/or a briefer vowel in BAT than in BAD. The types of enhancement that might be carried out for such cues would be shortening the duration of the vowel in BAT or increasing the intensity of the murmur in the /d/ of BAD.

Such speech-enhancing hearing aids are envisioned only for the future, because they will require speech recognition technology sufficiently advanced to operate in real time on continuous speech. Currently, speech recognition devices are successful only for brief phrases or words spoken with pauses intervening. Nevertheless, it is important now to study the feasibility of speech cue enhancement; this can be accomplished using computer-aided hand editing of selected test words.

We and others are engaged in studies of the benefits of speech cue enhancement for the hearing impaired (1, 4, 6, 7, 10, 11, 14). In our studies of speech cue enhancement thus far, we have investigated the perceptual effects mostly for hearing-impaired listeners with severe/profound losses. For listeners with this degree of impairment, often per-

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ception may be reduced for all of the linguistic articulatory features of consonants, that is, place, manner, and voicing. We have chosen to study enhancement of cues to consonant voicing first, because some of the voicing cues may be more amenable to machine detection and enhancement than cues to consonant place and manner. In addition, the voicing feature is a very frequent consonant distinction, as revealed by studies of conversational speech (2, Table 7.3).

The perception of voicing for word-final English consonants involves the detection and discrimination of both temporal and spectral speech-cue patterns. Serving as temporal cues are the preceding-vowel duration and the consonant-constriction duration (3), while the formant trajectories (transitions) in adjacent vowels and the presence of a voiced murmur during occlusion provide spectral cues (5,15).

In the present experiment we studied severely/profoundly hearing-impaired listeners for their voicing perceptions of word-final stop consonants with and without enhancement of cues associated with the stop constriction and release. The enhancements were amplification of the murmurs during the occlusions of voiced stops, and amplification of the release bursts of voiceless stops. Training of stop voicing perception was implemented for the words with enhanced stops and with the natural stops.

METHOD

Stimuli. Unmodified words (natural final stop constriction cues) and enhanced words (amplified constriction cues) were used as the stimuli to test final stop voicing perception. The unmodified stimuli were four different utterances each of the words /bæk/, /bæt/, /bæg/, and /bæd/, selected from a recording by a female talker. The words had been spoken separately at two different rates, yielding utterances with natural variation in spectral characteristics (frequency and intensity), and considerable variation in word duration. The selected words were digitized (16.67 kHz sampling rate, 12-bit amplitude representation) for waveform display, segmentation, modification, and subsequent playback via PDP8 computer system. The word segments of vowel, stop occlusion, and burst were identified visually on the digitized waveforms (13). Mean duration and intensity characteristics of these segments are displayed in **Table 1**. By prior selection among the recorded words, the 16 utterances differed in vowel duration by a mean of only 5 ms between voicing cognate words (i.e., /bæk/, bæt/ versus /bæg/, /bæd/), thus eliminating the possibility of stop voicing perception based upon the vowel duration cue. [To effect voicing perception of word-final consonants, the preceding vowel must be at least 30 percent longer for voiced consonants than for voiceless (3, 9)].

This set of unmodified utterances was used to prepare the stimuli with amplified stop constriction cues. To yield the enhanced /bæg, bæd/ utterances, the closure murmurs were amplified to approximate the level of the preceding vowels. The mean difference in intensity between the vowels and unmodified murmurs determined the amount of amplification for the murmurs (**Table 1**); each murmur was increased by 11 dB in the enhanced /bag, bad/ utterances. To obtain the enhanced /bæk, bæt/ utterances, the final release bursts were amplified by 14 dB, the maximum amount possible without peak clipping of the bursts. Thus, the enhanced /k,t/ bursts were an average of 3 dB below the syllables' vowels (**Table 1**). These amplifications were accomplished by software processing of the murmur or burst segment in the words, with no alteration to other segments therein.

Procedure. Prior to use of the stimuli described above, practice sessions were administered to familiarize each listener with the general test procedure. These sessions included presentation of at least 12 40-word identification tests, none of which used the enhanced or unmodified test stimuli.

Throughout the experiment, final stop voicing perception was tested for the unmodified and enhanced stimuli using a word identification procedure. The 16 utterances of the stimulus sets were each presented three times in random order among 48 single-interval word identification trials. No feedback of response accuracy was provided. Five response alternatives—"BACK", "BAT", "BAG", "BAD", and "BA"—were available via labeled pushbuttons on an answer box. The "BA" response alternative was provided for use in the event that the listener perceived no final consonant on a trial. The listeners were instructed to select the response that most closely resembled what (s)he heard. The test utterances were presented monaurally in each listener's better ear.

Table 1.
Means (and standard deviations) of segment durations and intensities for the unmodified words. For the enhanced words the intensities of the amplified murmurs and bursts are shown.

		Duration in milliseconds			Intensity (rms) dB re an arbitrary reference				
		Vowel	Stop occlusion	Release burst	Vowel	Stop occlusion (murmur)		Release burst (initial 25 ms)	
						Unmod.	Enh.	Unmod.	Enh.
BACK & BAT	*M*	239	111	47	50	20		33	47
	SD	(9)	(8)	(10)	(1)	(1)		(2)	(2)
BAG & BAD	*M*	244	67	49	51	40	51	33	
	SD	(12)	(12)	(14)	(1)	(2)	(2)	(2)	

The level of stimulus presentation for the enhanced and unmodified words was at each listener's most comfortable listening level (MCL). The MCL was established via an adaptive procedure in which the listener made judgements of TOO LOUD, TOO SOFT, or COMFORTABLE for numerous presentations, at different levels, of an isolated vowel from one of the words (11). An MCL was established at the beginning of each test session for each listener.

The word identification procedure was first used in the experiment to test baseline performance for stop voicing perception. One or two blocks each of the unmodified and the enhanced syllables were tested, typically in the initial experimental session.

Among most of the subsequent experimental sessions, training for stop voicing perception was implemented. In each training session, stop voicing perception was tested immediately before and after the presentation of several blocks of training trials. These trials enabled listeners to compare words in pairs that differed only for final stop voicing (10,11). The words used in training for a session were the same as those tested immediately before and after training.

During the training phase, the initial 2 to 4 sessions were usually devoted to the enhanced words, and about 2 subsequent sessions to the unmodified words. Fewer sessions were used for the unmodified words in order to minimize listeners' frustration, as only small improvements in stop voicing perception were evident for these words. The number of training sessions differed among listeners, particularly for the enhanced words. Subsequent to the second training session with the enhanced words, typically, additional training sessions were administered only for listeners whose after-training scores were below about 95 percent.

Final tests of stop voicing perception for the enhanced and unmodified words were administered during the latter sessions for some listeners. These tests were to discover how well performance could be maintained once training trials were discontinued. Overall, each subject participated in about 10 50-minute listening sessions during a period of 5 or 6 weeks.

Listeners. Twenty severely/profoundly hearing-impaired Gallaudet University students were participants in this study. Their threshold averages for 500, 1000, and 2000 Hz tones ranged from 71 dB to 110 dB, with a mean of 94 dB HL. The listeners were selected to have hearing losses that were severe or greater, because previous findings had indicated that reduced consonant voicing perception was a likely consequence of such losses (12, 13).

RESULTS

The listener's performances for stop voicing perception, tested at different times throughout the experiment, are summarized in **Table 2**. The scores represent perception of the stops according to

Table 2.
For 16 hearing-impaired listeners, means and standard deviations of percent correct stop voicing perception for /t,k,d,g/ in words unmodified or with amplified (enhanced) final stop constriction cues.

		Baseline tests	Tests before training	Tests after training	Final tests (n = 8)
Unmodified	*M*	58.4	64.2	68.7	65.4
	(*SD*)	(10.2)	(10.9)	(12.9)	(9.5)
Enhanced	*M*	61.8	80.1	90.7	97.4
	(*SD*)	(13.1)	(14.2)	(10.3)	(2.1)

whether they were recognized correctly for voicing. For example, a response of "back" for presentation of "bat," or vice versa, would be scored as correct for voicing. Each score shown in **Table 2** represents the listeners' mean performance across /t,k,d,g/ because perceptibility of voicing was similar among the stops throughout the experiment, $F(3,45)=0.6, p>.05$. The significance of differences in the results was tested by analysis of variance for repeated measures, followed by Tukey's test of honestly significant differences (q) to perform pairwise comparisons. The percentage scores underwent arc sine transformation prior to statistical analyses.

The scores in **Table 2** represent performances for 16 of the listeners who received training both for the unmodified and the enhanced words. The scores are not included for 4 other listeners who received no training for the enhanced words because of very good performance, or no training for the unmodified syllables because of very poor performance for the enhanced words.

Enhanced versus unmodified stop voicing perception. The enhanced words yielded considerably better perception of final stop voicing than the unmodified words, $F(1,15)=27.9, p<.01$, except at the beginning of the experiment. For the baseline tests, scores were similar between the enhanced and unmodified words, $q(6,30)=0.8, p>.05$. The mean baseline scores for the listener group differed by less than 4 percent between the enhanced and unmodified words, and were lower than scores obtained later in the experiment. Thus, upon initial presentation of the enhanced words, the group of listeners appeared to receive little benefit to perception of stop voicing from amplification of the stop constriction cues.

A substantial increase occurred in final stop voicing perception for the enhanced words relative to unmodified words during the training phase. Mean scores were 16 percent higher for the enhanced than for the unmodified words, $F(1,15)=26.2, p<.01$, among the tests administered immediately before training. For the tests after training, the enhanced words yielded scores that were an average of 22 percent above those of the unmodified words, $F(1,15)=31.0, p<.01$. These performance differences reveal that stop voicing perception was improved via amplification of stop constriction cues, and that the training facilitated the improvement in perception.

The performance superiority of the enhanced words relative to the unmodified was maintained at the end of the experiment for the subgroup of 8 listeners tested subsequent to the training phase. On the final tests, this subgroup obtained scores that were 32 percent higher for the enhanced than for the unmodified words. These final test scores were similar to the test scores after training for this subgroup, $q(4,21)=0.2, p>.05$, indicating that the performance differences between the enhanced and unmodified words did not decline following the training phase.

Training effects. As a result of the training, stop voicing perception appeared to improve considerably for the enhanced words, and only somewhat for the unmodified words. Relative to the baseline performances (**Table 2**), the scores immediately after training were about 29 percent higher for the enhanced words, $q(3,30)=6.5, p<.01$, and 10 percent higher for the unmodified words, $q(3,30)=2.3, p>.05$. The listeners' poor performances on the baseline tests were probably not caused by limited practice in test-taking, because all listeners had been admin-

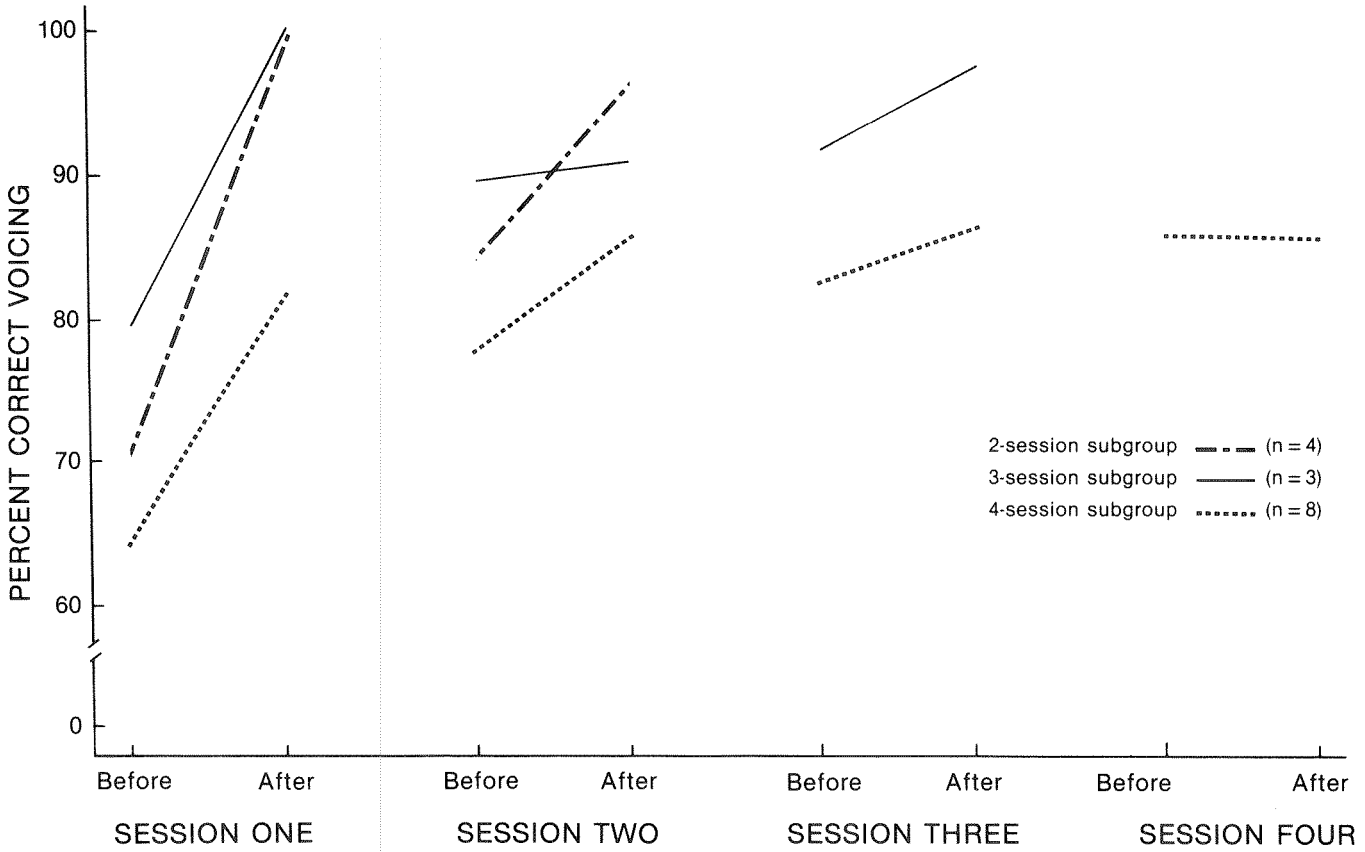

Figure 1-A.
For listener subgroups who received different amounts of training, mean percent correct final stop voicing tested before and after training per session for the enhanced words.

istered a word-identification screening battery comprising 12 40-word tests prior to the beginning of the experimental test sessions.

A comparison of the listeners' mean scores before versus after training does not reveal the maximum improvement for given training sessions because these scores represent performances averaged over successive training sessions. To learn whether the training effects occurred gradually or immediately, listeners' performances were examined among individual sessions. Scores for stop voicing perception throughout training are plotted for subgroups of listeners according to the number of training sessions they received for the enhanced words (**Figure 1-A**) and for the unmodified words (**Figure 1-B**). The listener subgroups are labeled "1-session," "2-session," etc., depending on the amount of training administered. Recall that the number of training sessions varied between the unmodified and enhanced words; thus given listeners may be in different subgroups for the enhanced versus modified words.

The first training session yielded the largest improvements and generally the highest level in stop voicing perception. For the enhanced words (**Figure 1-A**), the scores after training in the first session were a mean of 21 percent higher than before training, $t[15]=5.3, p<.01$. Between the first and second training sessions, performances declined; the enhanced-word scores before training in the second session were an average of 8 percent below those after training in the first session, $t[14]=1.9$, $p<.05$. Further, the maximum performance levels were somewhat lower in the second session than in the first, especially for the 2-session and 3-session subgroups. The 4-session subgroup obtained only a slight increase in after-training scores for the second versus first sessions, $t[7]=0.65, p>.05$. Note that this subgroup, who showed the lowest mean performance for the enhanced words, was generally unable to perform as well as the other subgroups who received fewer training sessions.

For the unmodified words also (**Figure 1-B**), the first training session produced the largest improve-

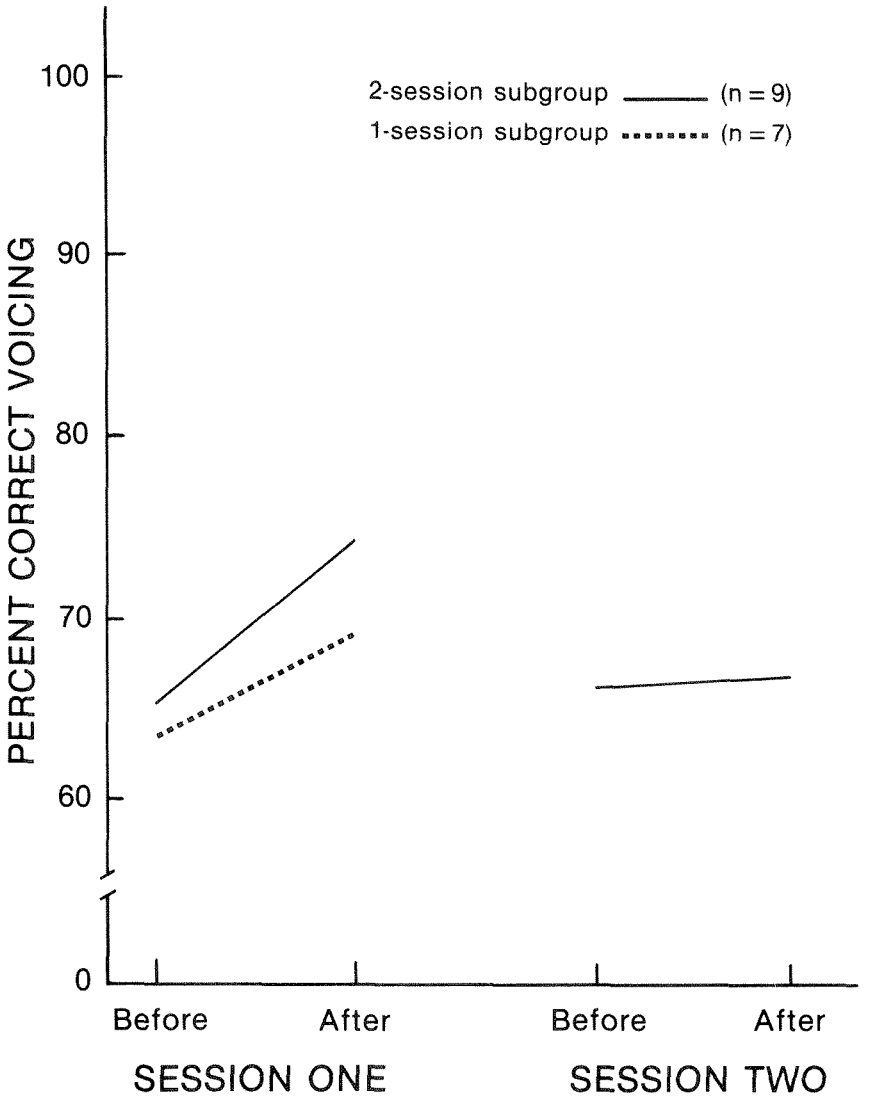

Figure 1-B.
For the unmodified words, mean percent correct final stop voicing before and after training by two listener subgroups who, respectively, received 1 or 2 sessions of training.

ment and best stop voicing perception. The scores after training were a mean of 7 percent higher than before training in the first session, $t[15]=3.33$, $p<.01$. The subgroup of 9 listeners who received a second training session showed no mean performance change before versus after training, $t[8]=.01$, $p>.05$, and the improvement obtained in the first session was not carried over to the second session. Time constraints and listeners' frustrations in distinguishing the unmodified words were factors influencing the limited number of training sessions administered for these words.

The difference in training effects between the enhanced and unmodified words is possibly related to the relative salience of the stop constriction cues. The performance changes during training for the unmodified words are similar to those found in a previous experiment on vowel-duration enhancement, where scores increased during training for words with unmodified vowels (11). However, those changes may not have been a direct effect of training, as additional small increases in scores occurred subsequent to the training stage.

Cue audibility among listeners. An important part of our cue enhancement research is to examine whether a given cue enhancement will be equally

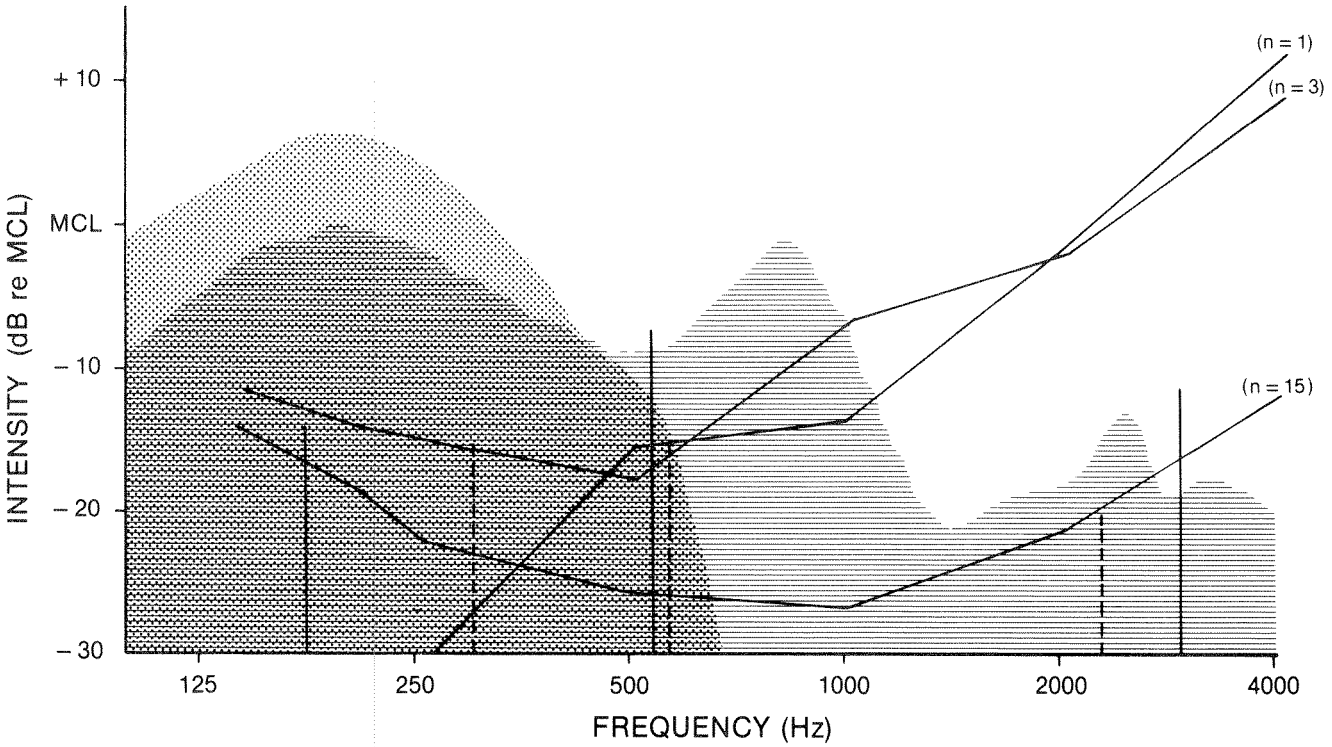

Figure 2.
Listeners' tone sensitivity contours (dB SPL) relative to MCL, and mean spectral levels of stimulus segments from the enhanced words. Tone contours represent listeners with stop voicing scores above 90 percent (n = 15) and listeners with scores below 80 percent (n = 3) and (n = 1). The dotted area represents the vowel spectra, and the cross-hatched area the murmur spectra. Vertical solid and dashed lines represent the three most prominent peaks of the enhanced /k/ and /t/ bursts, respectively.

beneficial among hearing-impaired listeners. In this experiment, for example, we wished to determine whether the 11-dB amplification of the murmur and the 14-dB burst amplification yielded good stop voicing perception across the listeners generally. Recall that these amplifications raised the murmur intensities approximately to the level of the words' vowels and the bursts to within about 3 dB of the vowels.

For the enhanced words, the distribution of stop voicing perception scores (either "after training," or "final" when after-training scores were not available) representing all 20 listeners revealed that three-quarters of the group performed at a level of 90 percent or better, while the remaining quarter of the group obtained scores ranging from 60 to 80 percent. Between these two subgroups, the performance difference generally seemed related to the stimulus presentation levels used and the resultant audibility of the enhanced stop constriction cues.

Among the 15 listeners scoring well, individuals' average MCLs used for presentation of the test words ranged from 104 to 127 dB SPL (mean = 118 dB). These presentation levels were an average of 22 dB (range 26 to 15 dB) above the listeners' detection thresholds measured for the [æ] vowel stimulus that was used in obtaining the MCLs. In contrast, among the 5 listeners who scored 80 percent or lower on the enhanced words, 3 used MCLs that were no more than 10 dB above threshold relative to the [æ] stimulus, and one other had tone thresholds that fell precipitously at frequencies above 250 Hz. A standard index of audibility is sensation level (SL), which is the difference in sound level between a test stimulus and the listener's threshold level of detection for that stimulus. Because these listeners heard the words' vowels at low SLs, it is probable that the enhanced murmurs and bursts were also at low SLs or perhaps subthreshold, depending on listeners' hearing sensitivity at the

frequencies of prominent energy in the murmurs and bursts.

Between the high- and low-scoring subgroups, the approximate differences in audibility of the word segments can be examined through plots of the segment spectrum levels versus the listeners' tone thresholds. **Figure 2** displays the mean spectrum levels of segments representing the 16 utterances, as measured via Fourier (FFT) analysis. The analysis windows were approximately 12.8 ms and included 213 digitized sample points. The measurements were made for the vowels at an average of 11 pitch periods from onset; for the murmurs, at approximately 2 pitch periods from murmur onset; and for the bursts, at the onset of the burst release. In **Figure 2** the segments are represented by a dotted area for the vowel spectra, a cross-hatched area for the murmur spectra, and vertical lines for the prominent spectral peaks of the bursts.

In addition to the segment spectra displayed in Figure 2, mean tone thresholds (converted from dB Hearing Level to dB SPL) are plotted relative to MCL for the high-scoring subgroup (n = 15) and in the low-scoring subgroup, for the listeners whose /æ/ SLs were 10 dB or less (n = 3) and for the listener with a quite precipitous tone threshold contour (n = 1). (Tone thresholds were unreliable and are not shown for the remaining listener in the low-scoring group. He was the best-performing member of this subgroup, with stop voicing perception at 80 percent.) The vertical placement of the tone sensitivity contours is based on the listeners' thresholds at 250 Hz, which showed the highest relation to the listeners' thresholds for the /æ/ vowel, $r(20) = 0.65$, $p < .01$, in comparison with thresholds at other audiometric frequencies.

The difference in the /æ/ SLs used by the subgroups is generally reflected by the distance of the vowel spectral peaks above the thresholds of the subgroups. For the high-scoring subgroup (n = 15, average [æ] SL of 22 dB), the /æ/ spectral peaks are about 20 to 30 dB above tone thresholds. For the low-scoring subgroup (n = 3, [æ] SLs of 10 dB or less) the /æ/ peaks are about 10 to 15 dB above tone thresholds. Also representing the low-scoring group is the listener with a quite precipitous tone threshold contour (n = 1, [æ] SL of 31 dB) who received the low-frequency peak of /æ/ at least 30 dB above threshold.

The line spectra representing the stop bursts reveal that these segments were more audible for the high-scoring than the low-scoring subgroup. In the frequency region of the bursts' highest energy (around 550 Hz), the /k/ and /t/ were heard an average of at least 10 dB above threshold for the high-scoring group, but less than 10 dB above threshold for the low-scoring group. The burst spectral peaks at other frequencies were at or near threshold for the high scoring subgroup, and generally below threshold for the low-scoring subgroup (n = 3), except for the listener with the precipitous threshold contour (n = 1). Although the low-frequency energy in the bursts seems clearly audible for this listener, apparently it was insufficient to yield a high level of stop voicing perception; his score for the enhanced voiceless stops averaged only 73 percent. The very poor distinction found for stop place of articulation, that is, between /k/ and /t/ and between /d/ and /g/, even by listeners in the high-scoring subgroup, is explained by the limited audibility of secondary spectral peaks of the bursts.

The dominant spectral peak of the murmur is at least 15 dB above threshold among the listeners generally. For the low-scoring listeners, the apparent audibility of the murmur would suggest that these listeners might obtain good performance for the enhanced voice stops. However, their scores after training for the enhanced voiced stops were only somewhat higher than those for the enhanced voiceless stops, respectively, 73 percent versus 68 percent. Perhaps the listeners' reduced use of the enhanced murmur as a cue was related to poor auditory frequency resolution wherein the auditory filtering mechanism may be abnormally broad, interfering with the listeners' ability to integrate the energy throughout the frequencies of the murmur.

DISCUSSION

This experiment revealed that amplification of stop constriction cues resulted in average improvements of about 22 percent for perception of voicing for word-final stop consonants by severely/profoundly hearing-impaired listeners. When the stop constriction cues were at their natural intensities in the words, these listeners exhibited mean voicing perception of the stops at less than 70 percent. The

perceptual gains realized for these stop cue enhancements approximate the gains found in an earlier experiment on consonant voicing perception as a result of enhancement of the vowel-duration cue (10, 11). However, the improvements of the present experiment are somewhat higher than gains seen for amplification of frication for final fricative consonants tested for some of the same listeners (10). The smaller improvements for the fricative consonants may be related to the effects of spectral filtering of the fricative consonants, which was used as an enhancement technique in addition to amplification. For the filtered fricative consonants, the resultant atypical sound quality could have lessened the amount of improvement.

In other research on consonant cue enhancement, hearing-impaired listeners with mild/moderate losses obtained 10 to 15 percent improvements in perception for syllables with amplified consonants and consonant-vowel transitions when the syllables were heard at low presentation levels; smaller improvements were seen at higher presentation levels (6). The improvements in consonant perception represented phoneme recognition, that is, correct place, manner, and voicing recognition, (in contrast to the results reported here where only correct stop voicing was considered). When stop phoneme recognition was examined for our listeners, improvement averaged 13 percent between the enhanced versus unmodified words tested after training. However, even for the enhanced words the listeners' performance levels were poor (mean = 49 percent) for stop phoneme recognition.

In the present study, different cues were chosen for amplification between the voiced and voiceless final stops: for /d,g/—the occlusion murmurs, while for /t,k/—the consonant bursts. Respectively, these segments were amplified by 11 dB and by 14 dB, which increased their overall levels to approximate the level of the vowels in the syllables. The perceptual gains yielded by these amplifications were similar between the voiced and voiceless stops.

Most of our listeners achieved similar high performance levels as a result of the stop cue amplification. The listeners' ability to use the amplified cues seemed to depend on cue audibility. Among the listeners who performed well, the dominant spectral peaks of the amplified bursts were generally estimated to be at least 10 dB above threshold. Conversely, for a small group of listeners who exhibited little perceptual improvement, the peaks of the amplified bursts were closer to threshold or completely inaudible. The spectral peak of the amplified murmur was at least 15 dB above threshold for high- and for low-scoring listeners. The inability of the low-scoring group to make use of the murmur cue for perception of the voiced stop may be related to abnormally broad auditory filtering mechanisms.

Training for stop voicing perception seemed important for most listeners in obtaining maximum performance, both for the enhanced and the unmodified syllables. However, the training resulted in substantially larger performance increases for the enhanced words than for the unmodified. Only one training session appeared necessary to yield listeners' maximum performances.

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