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Enhancement of Consonant Recognition in Bimodal and Normal Hearing Listeners

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Abstract

Objectives: The present study investigated the effects of 3-dimensional deep search (3DDS) signal processing on the enhancement of consonant perception in bimodal and normal hearing listeners.

Methods: Using an articulation-index gram and 3DDS signal processing, consonant segments that greatly affected performance were identified and intensified with a 6-dB gain. Then consonant recognition was measured unilaterally and bilaterally before and after 3DDS processing both in quiet and noise.

Results: The 3DDS signal processing provided a benefit to both groups, with greater benefit occurring in noise than quiet. The benefit rendered by 3DDS was the greatest in binaural listening condition. Ability to integrate acoustic features across ears was also enhanced with 3DDS processing. In listeners with normal hearing, manner and place of articulation were improved in binaural listening condition. In bimodal listeners, voicing and manner and place of articulation were also improved in bimodal and hearing aid ear-alone conditions.

Conclusions: Consonant recognition was improved with 3DDS in both groups. This observed benefit suggests 3DDS can be used as an auditory training tool for improved integration and for bimodal users who receive little or no benefit from their current bimodal hearing.

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Declaration of Conflicting Interests

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Keywords

bimodal integration; bimodal hearing; consonant enhancement; electric acoustic stimulation

Introduction

Bimodal (BM) hearing, consisting of a cochlear implant (CI) in 1 ear and a hearing aid (HA) in the contralateral ear, is a widely accepted clinical recommendation for listeners with residual hearing. A significant BM benefit, a performance difference between BM hearing and better ear alone, is well documented in speech and music perception over both preoperative listening conditions with binaural HAs and unilateral CI.^{1–3} However, this BM benefit greatly varies across BM users; some BM users experience little to no BM benefit, and some experience interference.^{2–5} There is a need to enhance speech perception in BM users who receive little or no benefit.

Li and colleagues^{6–8} and Kapoor and Allen⁹ showed that their signal processing scheme, 3-dimensional deep search (3DDS), is effective in enhancing acoustic cues for consonant recognition in normal hearing (NH) populations. The 3DDS requires 2 components to be successful: (1) an audibility prediction model and (2) speech perception measure outcomes in relation to 3 dimensions (frequency, time, and signal-to-noise ratio [SNR]). For the first component, they developed an articulation-index (AI) gram as a tool to predict audibility in the presence of noise.¹⁰ For the second component, consonant perception scores were measured with high- and low-pass filtering (frequency dimension), different amounts of consonant onset truncation (time dimension), and different SNRs (SNR dimension).^{6–9} Consonant perception scores under each of the 3-dimensional experiments were then paired with the AI gram to determine how each of the 3 dimensions affects the audibility of consonant perception. For instance, if /ba/ is presented at a certain SNR and perception scores drop significantly from 90% to 40% when the high-pass filter cutoff is moved from 1 kHz to 2 kHz, this indicates that important spectral cues reside between ~1 kHz and 2 kHz. Analogously, if perception scores for /ba/ drop significantly when the time-truncation point for voiced onset of consonant increases from 10 ms to 15 ms, it suggests that important spectro-temporal cues reside within the 10- to 15-ms time window. Additionally, for the SNR dimension, if performance on /ba/ perception drops significantly when SNR decreases from –5 dB to –10 dB, this suggests the audibility of the acoustic cues identified by 3DDS for /ba/ is not maintained under –10 dB SNR. Kapoor and Allen⁹ applied this approach and showed improved consonant perception in NH listeners with a 6-dB gain added to the spectro-temporal regions 3DDS identified at specific SNR, based on the 3 dimensions.

These findings in NH listeners leads to a question of whether a similar approach can be applied to listeners with hearing impairments, in the HA, CI, or even BM hearing case. If so, and both an HA ear and a CI ear can detect cues identified and enhanced by 3DDS, it could lead to improved integration within the central auditory system, thereby resulting in a greater BM benefit. The purpose of the following study was to apply this 3DDS method and determine whether the use of the 3DDS processing tool in this context does in fact enhance consonant perception in adult BM users and NH listeners.

Methods

Subjects and Stimuli

Nine BM adults (3 females and 7 males; range, 25–77 years, mean = 60.6 years) and 13 NH adults (8 females and 5 males; range, 20–57 years, mean = 32 years) participated in this study. All participants were native American English speakers. All BM subjects had at least 1 year of prior BM hearing experience. All NH listeners had thresholds better than 20 dB HL at audiometric frequencies. BM listeners' demographic data are given in Table 1. All subjects provided informed consent, the consent was written, and all procedures were approved by the Texas Tech University Health Sciences Center Institutional Review Board (IRB No. L14–048). Both subject groups were presented with 14 of the most frequently used consonants in American English. The consonants were produced by a female talker and were presented in a random order, in /CV/ context with a common vowel /a/ preceded by the consonants (/b/, /d/, /g/, /p/, /t/, /k/, /m/, /n/, /f/, /s/, /ʃ/, /v/, /z/, and /dʒ/).¹¹

3DDS and AI gram

The AI gram used in this study was implemented on the Matlab platform following procedures described by Li et al⁶ and Regnier and Allen.¹⁰ Using the acoustic cues identified by Li and colleagues^{6–8} and Kapoor and Allen⁹ as a guideline, we manually searched, using the AI gram, for the segment of each of the 14 consonants at +12 dB SNR that was most critical for the correct perception. As suggested by Li and colleagues^{6–8} and Kapoor and Allen,⁹ the segments were identified in noise (ie, +12 dB SNR) to include a realistic listening situation in 3DDS processing. We used tokens recorded by the same female talker (f103) as used in Li and colleagues,^{6–8} making it relatively straightforward to identify the critical segments. For segments identified by Li and colleagues^{6–8} that were produced by talkers other than f103, we used spectral ranges and temporal segments identified and averaged over multiple talkers. Once the crucial frequency band was identified, we applied a 6-dB gain to that band. To identify the temporal segment, we first identified the onset of the vowel /a/ by visually inspecting the spectrograms for each phoneme and verifying the onset point by listening to the consonant and vowel portions separately. We set the vowel onset at 0 ms, searched for the crucial consonant time segment, and applied a 6-dB gain to the identified segment (eg, from 10 ms to 25 ms prior to vowel onset). The end result in each case was a syllable that was significantly enhanced in terms of intelligibility. The completed 3DDS process was verified by 5 NH adult listeners, presenting each of the 14 3DDS-enhanced consonant syllables 30 times in random order. The consonants were presented in quiet conditions to both ears, with listeners identifying the phoneme they heard on a computer screen. Each processed sound was accepted when the error rate was less than chance level. The resultant frequency ranges and temporal segments to which we added 6-dB gain for all 14 consonants are given in Table 2.

Procedure

In this study, consonant recognition was measured in noise at –30, –25, –20, –15, and –10 dB SNR in the NH group. In the BM group, it was measured at +5, +10 dB SNR, and in quiet conditions. A steady-state, speech-shaped noise was generated as a masker with a low-pass cutoff of 1 kHz (–12 dB/octave). This noise masker was added to speech stimuli to

generate the designated SNRs. The choice of these SNRs for the NH group was based on our pilot data and was used both to validate the benefits of 3DDS processing and avoid a ceiling effect. The SNRs for the BM group were based on our previous studies.^{2,3} The stimuli were presented in a soundproof booth by a sound-field speaker for both groups. Both groups were tested under 3 listening conditions: left ear alone, right ear alone, and both ears. Additionally, the hearing device on the non-test ear was off and removed, and the non-test ear was occluded with a foam hearing protective device and headphones. During testing, subjects were instructed to select the consonant sound they thought they heard or make their best guess if they were unsure. Consonants were randomly presented. Each consonant was randomly presented 10 times at each SNR, and all subjects completed 2 runs under each listening condition at each SNR. This complete protocol was administered in 2 sessions: first before 3DDS (ie, without signal enhancement) and then after 3DDS (ie, with signal enhancement).

Results

The top panels of Figure 1 show 3DDS benefit for NH and BM listeners for unilateral and bilateral listening conditions as a function of SNR. Average absolute percentage scores are provided in the tables embedded in the top panels of Figure 1. The first numbers in the parentheses indicate the average percentage score after 3DDS signal processing, and the second numbers in the parentheses indicate the average score before 3DDS. The 3DDS benefit is the difference between the 2 numbers, expressed in percentage correct. This benefit was analyzed with a 2-way repeated measure analysis of variance (RMANOVA) with a significant level of $P = .05$. For NH listeners, a significant main effect of SNR was found, $F(4, 180) = 10.80$, $P < .001$. Post hoc Sidak pairwise comparisons showed a significantly different 3DDS benefits between SNRs ($P < .01$ in all cases), except between -10 and -15 dB SNR and between -20 and -25 dB SNR. There was no main effect in listening condition, $F(2, 180) = 0.14$, $P = .90$, and no significant interaction between listening conditions and SNR, $F(8, 180) = 0.58$, $P = .79$. For BM listeners, the 2-way RMANOVA analysis produced a main effect of listening condition, $F(2, 45) = 3.31$, $P < .05$. Post hoc Sidak pairwise comparisons showed that the average 3DDS benefit was significantly higher for the CI+HA combined than for CI alone but not HA alone ($P < .05$). However, the main effect of SNR was not significant, $F(2, 45) = 1.98$, $P = .150$, and interaction effect was non-significant as well, $F(4, 45) = .44$, $P = .782$.

To quantify how 3DDS signal processing affects the ability of BM and NH listeners to integrate consonant acoustics across ears, integration efficiency (IE) was computed using
$$IE = \frac{P_l + P_r - P_l P_r}{P_b}$$
, described by Fu et al¹² and Yang and Zeng.¹³ In this equation, P_l is the probability of left ear alone performance, P_r is the probability of right ear alone performance, and P_b is the probability of binaural performance. To quantify how integration was affected by 3DDS and the various SNRs, we again conducted separate 2-way, 3DDS $\times$ SNR RMANOVAs for NH and BM groups; results are shown in the two bottom panels of Figure 1. For NH listeners, a significant main effect of 3DDS processing, $F(1, 120) = 64.41$, $P < .001$, and of SNR, $F(4, 120) = 34.49$, $P < .001$, was found, suggesting that 3DDS processing contributed to improved integration efficiency. Post hoc pairwise comparisons

using the Sidak pair-wise comparisons showed significantly better IE between -10 and -15 dB SNR and between -20 and -25 dB SNR ($P < .01$ in all cases). The interaction was not significant, $F(4, 120) = 0.92$, $P = .45$. For BM listeners, 2-way RMANOVA analysis showed that IE was significantly higher after 3DDS than before 3DDS, $F(1, 30) = 4.10$, $P < .05$. However, there was no significant effect of SNR, $F(2, 30) = .386$, $P = .683$, and no significant interaction between SNR and 3DDS conditions, $F(2, 30) = .106$, $P = .90$.

Figure 2 shows the information of the acoustic features (voicing, manner, and place) transmitted after 3DDS compared to before 3DDS. To show the trend of 3DDS benefit, information transmitted was averaged across SNR in both groups. For NH listeners, the 2-way RMANOVA shows a significant main effect of listening condition, $F(2, 108) = 35.09$, $P < .001$. Post hoc Sidak pairwise comparisons showed a significant difference between binaural and unilateral listening conditions after 3DDS ($P < .001$ in all cases) but not between unilateral listening conditions. The amount of information transmitted was also significantly different across the acoustic features, $F(2, 108) = 24.30$, $P < .001$. Post hoc Sidak pairwise comparisons showed that any pair comparisons between the acoustic features were significantly different ($P < .02$ in all cases). There was also significant interactions between listening conditions and acoustic features, $F(4, 108) = 3.37$, $P = .01$.

For BM listeners, the 2-way RMANOVA shows a significant main effect of listening condition, $F(2, 45) = 35.80$, $P < .001$. Post hoc Sidak pairwise comparisons showed that any pair comparisons between the listening conditions were significantly different ($P < .02$ in all cases). The amount of information transmitted in the acoustic features was significantly different, $F(2, 45) = 8.96$, $P < .001$. Post hoc Sidak pairwise comparisons showed voicing was significantly better transmitted than place ($P < .001$). There was also significant interactions between listening conditions and acoustic features, $F(4, 45) = 4.39$, $P = .004$.

Discussion

By using the 3DDS signal processing tool, consonant recognition was measured in adult BM users and NH users. Both groups received benefit from 3DDS processing, particularly under binaural hearing condition and at lower SNRs, and integration efficiency was significantly enhanced as well. The 3DDS processing enhanced the transmission of voicing, manner, and place information in binaural listening condition in both groups.

The 3DDS benefit, a performance difference between before and after 3DDS processing, in the NH listeners ranged from 8% to 11% at SNRs -20 dB and dropped to 4% at SNRs -15 dB across listening conditions. Kapoor and Allen⁹ reported the range of 10% to 70% 3DDS benefit at SNRs -6 dB but less than 5% at SNRs 0 dB. This general trend was observed in consonants produced by different talkers. Because such a wide range of the benefit in Kapoor and Allen⁹ was based on a few selective superior performers, direct comparisons between the 2 studies can-not be made. In our BM group, the 3DDS benefit ranged from 2% to 11%, with the highest benefit in BM listening condition to be first with a HA-ear alone and then a CI-ear alone. As in the NH group, the 3DDS benefit increased as the SNR decreased. This increasing 3DDS benefit with lowering SNRs might be because the conflicting acoustic cues are masked by noise, thus reducing perceptual confusion. The

effect of these conflicting cues under noisy environments is currently being investigated in our laboratory.

In the current study, BM benefits (from the inserted table in the top right panel of Figure 1), a performance difference of BM hearing from the better ear alone, were 12%, 7%, and 9% after 3DDS and 7%, 4%, and 4% before 3DDS at +5, +10, and in quiet. It denotes that true BM benefits (ie, a difference in BM benefits after and before 3DDS) were only 5%, 3%, and 5% in noise of SNRs at +5, +10, and in quiet, respectively. This small BM benefit with 3DDS processing contributed to a similar amount of 3DDS benefit from monaural (ie, a HA alone and a CI alone) and BM hearing. In the literature, BM benefit varied highly (8%–25%) depending on subjects, testing materials, and conditions.^{4,14} Yoon et al² tested BM listeners on consonant, vowel, and sentence perception at the same SNRs as in the current study. They observed a BM benefit of less than 5% from poorer performers, while ranging from 10% to 15% BM benefit in good performers regardless of testing materials, which is consistent with our current data.

In terms of acoustic features (voicing, manner, and place), 3DDS attributes to better transmission of manner and place in the NH group and to each of these 3 acoustic features for both HA-ear alone (7%, 4%, and 6%) and BM condition (8%, 7%, and 4.5%) in the BM group. Yoon et al² also showed that good BM performers received enhanced voicing (8%), manner (10%), and place (10%) while poorer performers received all 3 features at less than a 3% enhancement. Another observation in the BM group was that an HA ear better perceived and processed acoustically enhanced features by 3DDS than a CI ear. Our results suggest that 3DDS signal processing contributes to improving a wide range of spectral information via an HA ear and the spectral information could be integrated with information processed by a CI ear. It is clear that this acoustically enhanced feature was underutilized by a CI ear.

Since our study tested BM listeners without optimizing their clinical devices, it is highly likely that our subjects have various levels of spectral and temporal mismatch across ears. In the BM group, IE was higher after 3DDS processing than before and also increased with improving SNRs. Fu et al¹² demonstrated the relationship between IE and spectral mismatch using acoustic simulations of BM and electric acoustic stimulation (EAS; electric and acoustic signals are presented to 1 ear) listening configurations with NH listeners. Their results show a greater binaural benefit when spectral mismatch between acoustic and electric ears are minimized. Fu et al¹² also observed that IE in EAS simulation continuously increased with decreasing spectral mismatch while IE in BM simulation stayed consistently lower regardless of the spectral mismatch. These results suggest that spectral match may be more critical in EAS but not BM hearing. Based on this result, 3DDS benefits increase particularly in EAS listening when spectral mismatch reduces by mapping CI frequency maps according to frequency ranges in an HA ear.

There are a few limitations in this study. As 3DDS considers 3 dimensions (time, frequency, and SNR) of consonant +/a/ phonemes that cause dramatic change in the recognition score, other acoustic cues such as formant transitions, voicing, and voice onset time will not be captured by 3DDS. The possibility exists that these noncaptured cues may be determining factors for BM benefit. The articulation index-gram is modeled on a linearity of the cochlea,

which does not account for cochlear compression, forward masking, upward masking, or other well-known nonlinearities observed in the auditory nerve responses. At this point, we are forced to use this linear model of the articulation index-gram until a fully tested time-domain nonlinear cochlear model becomes available. Nevertheless, based on findings of Li and colleagues^{6–8} and Kapoor and Allen,⁹ the linear articulation index-gram provides a useful threshold approximation. Even though a 15-minute familiarization was provided, listeners with an HA ear alone or a CI ear alone were placed in an unusual listening condition. This discrepancy could be resolved by testing each listening condition after obtaining a patient's asymptote performance in quiet. Age differences between subject groups might be an extraneous variable even though both groups showed the ability to utilize enhanced acoustic cues for consonant recognition.

In conclusion, the 3DDS processing tool can identify important spectro-temporal segments of consonants to improve perception in NH and BM listeners. Integration can also be enhanced by presenting consonants processed by 3DDS. The 3DDS signal processing can be implemented into psychoacoustic evaluation tools that are feasible to use in order to quantify the success (or lack of improvement) of BM use and provide auditory training for BM users who receive little or no benefit from their current BM hearing.

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Figure 1.

Mean 3DDS benefit for (A) NH and (B) BM along with integration efficiency for (C) NH and (D) BM. On the 2 top panels, averaged performance scores are shown in the inserted table for each group. The first number in the parentheses indicates the mean scores after 3DDS processing, the second number indicates the mean scores before 3DDS processing, and the 3DDS benefit is the difference between these 2 scores for each listening condition and each SNR. Integration efficiency was plotted before and after 3DDS processing as well. Abbreviations: 3DDS, 3-dimensional deep search; BM, bimodal hearing; NH, normal hearing..

Figure 2.

Mean information transmitted on voicing, manner, and place for (left panel) the NH group and (right panel) the BM group as a function of listening conditions. To show the overall trend of the feature perception enhancement, data assessed at each SNR were averaged over SNRs tested for each group. Significance is indicated by asterisk.

Abbreviations: BM, bimodal hearing; NH, normal hearing; SNR, signal-to-noise ratio.

Table 1.

Subject Demographics.^a

ID (age, gender)	(PTA in dB HL)	Device	Years of Experience	Etiology	Device, Processor, Strategy	Presentation Level dB (A) SPL
S1		R: CI	11	Unknown	Nucleus 24, Freedom, ACE	70
(77, F)		L: HA	34	Unknown	Phonak, Savia	70
(76)		Both	II			65
S2		R: CI	I3	Rubella	Nucleus 24, Freedom, SPEAK	70
(44, M)		L: HA	43	Rubella	Phonak, 313	70
(43)		Both	I3			65
S3		L: CI	II	Unknown	120, Harmony, HiRes	65
(77, M)		R: HA	II	Unknown	Widex, Senso	70
(44)		Both	II			65
S4		R: CI	I	Unknown	Nucleus 24, Freedom, ACE	65
(73, M)		L: HA	36	Unknown	Phonex, CROS	70
(55)		Both	I			65
S5		L: CI	3	Otosclerosis	Nucleus 24, Freedom, ACE	65
(71, M)		R: HA	35	Otosclerosis	Simens ETE	70
(65)		Both	3			65
S6		L: CI	1.5	Meningitis	Nucleus 5, Freedom, ACE	65
(25, M)		R: HA	6	Meningitis	Phonak, Supero	65
(31)		Both	1.5			65
S7		R: CI	2	Ototoxicity	C2, Harmony, HiRes	70
(56, F)		L: HA	8	Ototoxicity	Widex Body	70
(56)		Both	2			70
S8		L: CI	3	Unknown	Nucleus 24, Freedom, ACE	65
(69, M)		R: HA	50	Unknown	Unitron, 360 +	70
(37)		Both	3			65
S9		L: CI	2	Unknown	Nucleus 24, Freedom, ACE	65
(47, M)		R: HA	42	Unknown	Simens, Centra	70
(38)		Both	2			65
S10		L: CI	7	Hereditary	3G, Freedom, ACE	65

ID (age, gender) (PTA in dB HL)	Device	Years of Experience	Etiology	Device, Processor, Strategy	Presentation Level dB (A) SPL
(67, F)	R: HA	37	Hereditary	Resound, Metrix	70
(70)	Both	7			65

^aR is right ear, and L is left ear. Abbreviations: ACE, Advanced Combination Encoder; Aided PTA, pure tone average for frequencies of 0.25, 0.5, 0.75, and 1 kHz in the acoustic side; CI, cochlear implant; HA, hearing aid; HiRes, high resolution; HL, hearing loss; SPEAK, spectral PEAK; SPL, Sound Pressure Level.

Table 2.

Frequency Ranges and Segments of Consonants on Which a +6-dB Gain Was Applied After Identified by 3DDS.^a

	lbal	ldal	lgal	lkal	lpal	ltal	lnal
Spectral ranges gained with +6 dB in kHz	0.3–4.5	>4	1.4–2	1.4–2	0.3–7.4	3–7.4	0.5–1.3
Temporal segment from onset of vowel /a/ in milliseconds	10–25	15–25	30–50	50–70	10–40	50–70	50–80
	lfal	l3al	lsal	lzal	lfal	lval	lnal
Spectral ranges gained with +6 dB in kHz	2–3.7	1.9–3.7	3.9–8	3.6–8	0.6–2.2	0.6–.4	1.5–2.2
Temporal segment from onset of vowel /a/ in milliseconds	80–200	45–70	75–175	40–70	65–100	20–50	30–80

^aFor instance, +6 dB gain on the sound /ba/ was applied at the frequency ranges between 0.3 kHz and 4.5 kHz and on the segment between 10 ms and 25 ms from onset of /a/ vowel. Abbreviation: 3DDS, 3-dimensional deep search.