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Original Article

Effects of the Simultaneous Application of Nonlinear Frequency Compression and Dichotic Hearing on the Speech Recognition of Severely Hearing-Impaired Subjects: Simulation Test

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Objectives. The clinical effects of the simultaneous application of nonlinear frequency compression and dichotic hearing on people with hearing impairments have not been evaluated previously. In this study, the clinical effects of the simultaneous application of these two techniques on the recognition of consonant-vowel-consonant (CVC) words with fricatives were evaluated using normal-hearing subjects and a hearing loss simulator operated in the severe hearing loss setting.

Methods. A total of 21 normal-hearing volunteers whose native language was English were recruited for this study, and two different hearing loss simulators, which were configured for severe hearing loss in the high-frequency range, were utilized. The subjects heard 82 English CVC words, and the word recognition score and response time were measured.

Results. The experimental results demonstrated that the simultaneous application of these two techniques showed almost even performance compared to the sole application of nonlinear frequency compression in a severe hearing loss setting.

Conclusion. Though it is generally accepted that dichotic hearing can decrease the spectral masking thresholds of an hearing-impaired person, simultaneous application of the nonlinear frequency compression and dichotic hearing techniques did not significantly improve the recognition of words with fricatives compared to the sole application of nonlinear frequency compression in a severe hearing loss setting.

Keywords. *Hearing Loss; Dichotic Listening Tests; Signal Processing, Computer-Assisted*

INTRODUCTION

Hearing-impaired (HI) persons with sensorineural hearing loss have several pathological symptoms, such as deteriorated time and spectral resolutions and abnormally high hearing thresholds, generally in high-frequency ranges [1]. As a result, intelligibility for words that contain consonants with a spectral power that is mainly placed in a high-frequency range (e.g., fricatives) become especially weak, and this requires the help of hearing support (HS) devices, such as digital hearing aids and cochlear implants, to improve the patient's intelligibility. Most HS devices utilize hearing-compensation algorithms (e.g., wide dynamic range compression [WDRC]) to selectively amplify the sound components in high-frequency ranges where the hearing thresholds are abnormally high. However, when the values of WDRC gain in high-frequency bands become too high at the severe hearing

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loss setting, the clipping phenomenon can be generated in the output signal of the WDRC [2], which deteriorates the speech intelligibility of an HI person. In addition, HI persons who have a dead zone at a specific high-frequency range cannot hear the sound components in the dead zone range at any values of the WDRC gain [3].

In order to improve the speech intelligibility of such severe hearing loss patients, two techniques have been suggested: nonlinear frequency compression and dichotic hearing. Nonlinear frequency compression aims to supply more sounds in high-frequency regions to HI persons with severe hearing loss in high-frequency regions by compressing the original sounds in high-frequency regions so that the inaudible sound components move to the lower-frequency range where the degree of hearing impairment is relatively low [4,5]. This technique enables HI persons with severe hearing impairment in high-frequency regions to hear the high-frequency sounds, unless they cannot hear anything. However, this technique can worsen these persons' ability to discriminate between fricatives (e.g., s, th, and f), whose spectral powers are similar to each other and are mainly in relatively high-frequency regions (approximately 3,000–4,000 Hz), because it reduces the separation between frequency components, and therefore, can worsen the intelligibility of words containing fricatives. The second technique, dichotic hearing, aims to improve the frequency selectivity of the HI person. The bandwidths of the native auditory filters of HI persons are generally wider than those of normal-hearing (NH) persons (i.e., spectral smearing), and therefore, the frequency selectivity of HI persons is relatively low. Several previous reports have demonstrated that dichotic hearing could reduce the spectral masking threshold and improve the frequency selectivity of HI persons [6]. Between these two techniques, the former can supply inaudible sounds in high-frequency regions to an HI person, but can also decrease the frequency selectivity of the HI person in high-frequency regions; in contrast, the latter can improve the frequency selectivity of the HI person, but cannot supply inaudible sounds in high-frequency regions. However, as far as we know, there has been no report that evaluated the clinical effects of the simultaneous application of these two techniques.

In this study, the clinical effects of the simultaneous application of the nonlinear frequency compression and dichotic hearing techniques on the recognition of words with fricatives were evaluated using 21 NH subjects and two hearing loss simulators operated in the severe hearing loss setting.

MATERIALS AND METHODS

Description of the utilized algorithms

In this study, three HS algorithms were implemented using MATLAB [7]: WDRC, nonlinear frequency compression, and dichotic hearing. For WDRC, the eight-channel side-branch WDRC algorithm suggested by Yasu et al. [8] was utilized. It was implemented so that the gain values of each frequency band were automatically calculated when the hearing threshold values of the subject were entered. For nonlinear frequency compression, the algorithm suggested by Simpson et al. [5] was utilized. In the implemented algorithm, the input frequency range was set to 0–8,000 Hz and the cutoff frequency was set to 2,000 Hz. The compression ratio in the region under the cutoff frequency was set to 1:1 (no compression) and the compression ratio in the region over the cutoff frequency was set to 1:3. Areas over the 4,000 Hz after compression were zero-padding processed (1,024- point Fast Fourier Transform with 50% overlap). For dichotic hearing, the nonlinear, comb filter-based dichotic hearing algorithm suggested by Cheeran et al. [9] was utilized. During implementation, the frequency range 1–5,000 Hz was divided into 18 frequency bands and gamma-tone filters with shapes similar to the real auditory filter, which were applied to each frequency band, as in Eq. 1:

$$g(t) = at^{n-1}e^{-2\pi bt}\cos(2\pi ft+\phi) \quad \text{Eq. 1}$$

where f represents the center frequency of the frequency band (Hz), ϕ represents the phase of the carrier (radians), constants a and b represent amplitude and bandwidth of the gamma-tone filter, respectively, n represents the order of the gamma-tone filter, and t represents the time (second). In this study, gamma-tone filters were generated using a MATLAB code suggested by Staney [10], and among the suggested four types of gamma-tone filters, the 'Moore' methodology was selected to generate the 18 gamma-tone filters that covered the 1–5,000 Hz region (the center frequencies of each frequency band were 75, 130, 195, 273, 364, 472, 600, 751, 930, 1,141, 1,391, 1,686, 2,035, 2,448, 2,935, 3,512, 4,194, and 5,000 Hz). Then, among the implemented 18 gamma-tone filters, the output signals of the nine odd filters (1st, 3rd, 5th, …, 17th) were added together and this summed signal was heard by the left ear; furthermore, the output signals of the nine even filters (2nd, 4th, 6th, …, 18th) were added together and this summed signal was heard by the right ear at the same time.

Settings for hearing loss simulators

In this study, two hearing loss simulators were utilized to simulate an HI person with severe hearing loss in the high-frequency region: a hearing loss simulator with threshold-adjustment ability (Hearing Loss and Prosthesis Simulator; Sensimetrics Co., Malden, MA, USA; denoted by HLS-1) [11,12] and a hearing loss simulator with both the threshold- and smearing-adjustment abilities (Cochclear Implant and Hearing Loss Simulator ver. 1.08.01; TigerSpeech Technology, Shanghai, China; denoted by HLS-2) [13,14]. For both HLS-1 and HLS-2, the hearing thresholds of each frequency band were set to 20, 20, 25, 35, 50, 85, and 90 dB hearing level for frequency bands 1, 2, …, and 7, re-

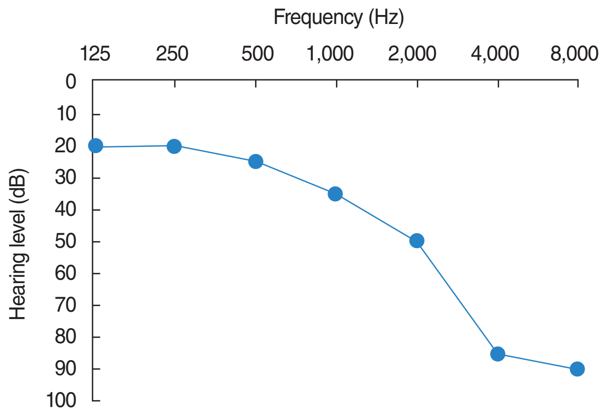

Fig. 1. Hearing threshold setting for both the HLS-1 and HLS-2 that simulates severe hearing loss in the high-frequency region. HLS, hearing loss simulator.

spectively (the center frequencies of each frequency band were 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz, respectively), based on the audiogram data of an HI person with severe hearing loss in the high-frequency region (Fig. 1) [15]. In addition, for HLS-2, the degree of spectral smearing was determined on the basis of a previous article by Glasberg et al. [16], which demonstrated that the bandwidth of the auditory filters of persons with severe hearing loss is approximately six times wider than that of an NH person. Based on the measurements of Glasberg et al. [16], the value of the HLS-2 smearing parameter was adjusted in order to examine the relationship between the value of the smearing parameter and the bandwidth of the HLS-2 output signal. That is, first, the smearing parameter value was set to zero (simulating the NH condition) and the bandwidth of the HLS-2 output signal when a 1-kHz pure-tone sine wave was entered into the HLS-2 was measured. Then, the same measurements were repeated with increasing smearing parameter values from 0.5 to 3.0 at 0.5 intervals (simulating HI conditions). Each output signal of HLS-2 was normalized and the difference between two frequency values with a normalized amplitude of 0.707 was regarded as the auditory filter bandwidth of HLS-2 (Fig. 2). In these measurements, the auditory filter bandwidth of the HLS-2 output signal at smearing parameter 2.5 was approximately six times wider than that when the smearing parameter was 0. On the basis of these measurements, the smearing parameter of HLS-2 was set to 2.5 during experiments.

Utilized sound sources and tested algorithm combinations

Sound files contained in the free-download software for the interactive listening rehabilitation and functional hearing test (Sound Express Auditory Training [SEAT]; TigerSpeech Technology) [17] were utilized in this study (16-bit quantization and 22-kHz sampling frequency). Among the thousands of sound files in the SEAT program, 216 consonant-vowel-consonant (CVC) English words that were utilized in the CVC word recognition test of House et al. [18] were initially extracted, and 82 CVC words

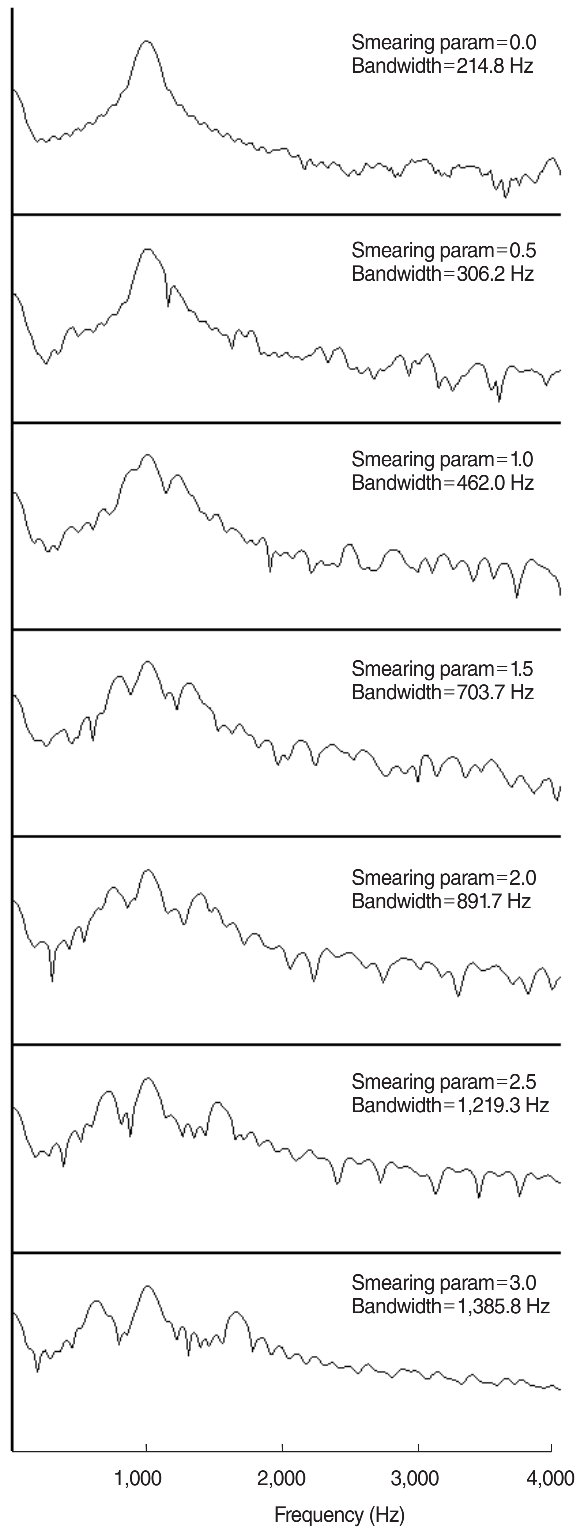

Fig. 2. Measurements of the HLS-2 bandwidth when a 1-kHz pure-tone sine wave was entered into HLS-2 and the values of the smearing parameter were adjusted from 0.0 to 3.0 at 0.5 intervals. HLS, hearing loss simulator.

Table 1. The 82 consonant-vowel-consonant English words selected for word recognition testing

Set	Training		Test	
	Male voice	Female voice	Male voice	Female voice
1	BAT	BAT	BATH	BASS
2	BEAM	BEAM	BEAN	BEAK
3	BUCK	BUS	BUS	BUFF
4	CAPE	CAVE	CASE	CAKE
5	CUP	CUFF	CUFF	CUSS
6	DIN	DIN	DILL	DIP
7	DUB	DUD	DUCK	DUN
8	FIT	FIZZ	FIN	FILL
9	HEATH	HEAP	HEAVE	HEATH
10	KIN	KICK	KIT	KICK
11	LATE	LAKE	LAKE	LATE
12	MAN	MASS	MATH	MASS
13	PALE	PAGE	PACE	PAVE
14	PACK	PAT	PASS	PATH
15	PEACE	PEAL	PEAT	PEAS
16	PIT	PICK	PICK	PIP
17	PUCK	PUB	PUS	PUFF
18	RAKE	RACE	RAKE	RACE
19	SAME	SAME	SAFE	SAKE
20	SAG	SACK	SASS	SAT
21	SEEM	SEEN	SEEK	SEEP
22	SIT	SICK	SIP	SICK
23	SUN	SUB	SUP	SUM
24	TAB	TAB	TAP	TAN
25	TEACH	TEAR	TEAM	TEASE
26	LED	LED	FED	BED
27	PIG	WIG	BIG	FIG
28	LICK	WICK	TICK	SICK
29	COOK	SHOOK	SHOOK	TOOK
30	TALE	MALE	PALE	SALE
31	KEEL	HEEL	FEEL	KEEL
32	HILL	BILL	KILL	TIL
33	FAME	CAME	SAME	FAME
34	HEN	THEN	TEN	MEN
35	DIN	WIN	FIN	SIN
36	GUN	SUN	SUN	FUN
37	RIP	LIP	SIP	HIP
38	SHOP	POP	MOP	SHOP
39	NEAT	HEAT	SEAT	FEAT
40	FIT	KIT	FIT	SIT
41	LOT	GOT	HOT	POT

from the extracted 216 words were then randomly selected, as shown in Table 1. Each of the sound files of the 82 CVC words that were ultimately selected were down-sampled to 16-bit quantization and 16-kHz sampling frequency conditions considering the hardware specification of the conventional HS devices. These down-sampled sound files were utilized for the clinical tests.

During the clinical tests, two different combinations of the testing algorithms were evaluated. First, the original sound was entered into the nonlinear frequency compression algorithm, the

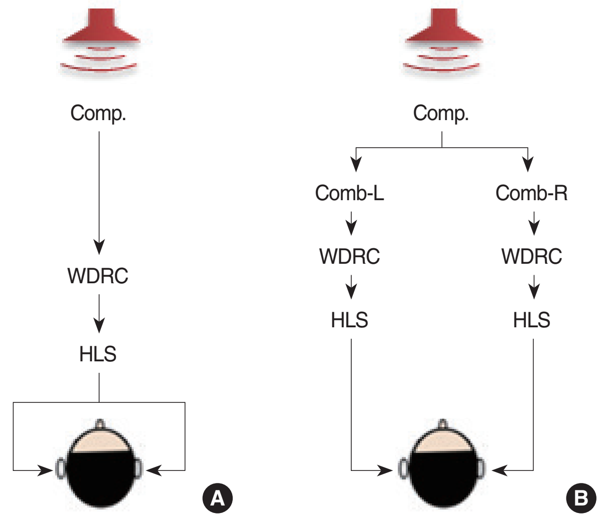

Fig. 3. Schematics of the combinations of testing algorithms: (A) TAC1. (B) TAC2. Comp., frequency compression; Comb-L, odd-band comb filter; Comb-R, even-band comb filter; WDRC, wide dynamic range compression; HLS, hearing loss simulator; TAC, testing algorithm combination.

output of the nonlinear frequency compression algorithm was entered into the WDRC algorithm, the output of the WDRC algorithm was entered into the HLS, and the output of the HLS was heard by the NH subject (same sounds in both ears; nonlinear compression only; denoted by testing algorithm combination 1 [TAC1]) (Fig. 3A). Second, the original sound was entered into the nonlinear frequency compression algorithm and the output of the nonlinear frequency compression algorithm was entered into the two different comb filters (odd-band filter and even-band filter). The output of the odd-band comb filter was processed using the WDRC algorithm and HLS, and the output of the HLS was heard by the left ear of the subject; the output of the even-band comb filter was processed using the WDRC algorithm and HLS, and the output of the HLS was heard by the right ear of the subject simultaneously (different sound in each ear; both nonlinear compression and dichotic; denoted by TAC2) (Fig. 3B).

For effective clinical tests, each of the selected 82 CVC words were pre-processed using each of the TAC1 and TAC2 combinations, and 328 sound files (164 files for HLS-1 and 164 files for HLS-2) were generated by recording the outputs of the simulators for each case. These were utilized during the experiments.

Participants

A total of 21 NH volunteers whose native language was English participated in this study. The recruited volunteers' audiogram values were measured using the pure-tone audiometry testing protocol using an audiometer (Digital audiometer; Digital Recordings, Halifax, NS, Canada) and a headset (AKG K-271 Mk2; AKG, Vienna, Austria). Among those whose values were under 25 dB HL at all testing frequency bands [19,20], 11 applicants (6 males and 5 females; mean age, 26.0 years; range, 22 to 43 years) participated in tests using HLS-1 and 10 applicants (4 males and 6 females; mean age, 24.8 years; range, 19 to 34 years) participated in tests using HLS-2. Detailed experimental protocols were approved by the local Institutional Review Board (IRB) of Hanyang University (HYU IRB HYI-12-048 for HLS-1 and HYU IRB HYI-13-120 for HLS-2). The content of the experiments was explained to each subject and written agreements were acquired before beginning the experiments, and each participant was paid a reward (approximately 30 United States dollars).

Experimental protocol

Clinical tests were performed in a sound-proof room (left×right×height: 300 cm×300 cm×200 cm) at Hanyang University. When each subject entered the testing room, the experimental procedures were explained and re-explained to each subject before beginning the experiments until the subject fully understood the content of the experiments. Then, the subject was asked to wear a headset (THD 39, GN Otometrics A/S, Taastrup, Denmark) with the volume preadjusted to 65 dB SPL (sound press level), and the experiment began. During both tests for HLS-1 and HLS-2, initial training was performed so that the subject became familiar with the content and procedures of the experiment. When the training began, one of the 82 CVC words contained in the second and third columns in Table 1 (no processed) was played and the subject was asked to select the word they heard among the six words displayed on the monitor in front of them. The same procedure was repeated 82 times (with all 82 words), and then the subject took a rest for three minutes before beginning the actual test. When the actual test began, 164 sound files representing the 82 CVC words in the fourth and fifth columns of Table 1 and two testing algorithm combinations (TAC1 and TAC2) were played one-by-one for either HLS-1 or HLS-2, and the subject was asked to select the word they heard among the six words displayed on the monitor. To reduce the training effect during successive experiments, words processed by TAC1 and TAC2 were randomly played and the gender of the voice (male or female) saying the words was also randomly selected. In addition, to reduce the listening fatigue of the subject, the subject took a rest for 30 seconds after 42 words had been tested.

After overall measurements, statistical analysis was performed only using the 34 words containing the fricatives s, f, and th either at the front or rear position among the 82 words. The calculations were performed using commercial software [21], and the nonparametric Mann-Whitney test was applied to the comparison between the two groups because the number of participating subjects was insufficient for a conventional *t*-test.

RESULTS

Clinical measurements when HLS-1 was utilized

Table 2 shows the correction ratio (%) of the target CVC words when HLS-1 was utilized. There was a statistically significant difference between (female voice, TAC1) and (female voice, TAC2)

Table 2. Measurements of the correction ratios (%) when HLS-1 was utilized

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Male voice									
TAC1	31.82±33.71	98.19±6.03	54.55±26.97	97.73±7.54	45.45±33.20	71.59±17.76	73.74±12.45	97.98±4.49	48.48±26.30
TAC2	22.73±34.38	94.55±9.34	45.45±26.97	84.90±30.15	52.27±32.51	72.73±15.63	67.68±15.28	89.90±13.57	50.00±24.72
Female voice									
TAC1	68.19±33.71	90.91±10.44	54.55±15.08	95.45±10.11	43.18±16.17	69.32±11.68	78.79±10.49	92.93±7.49	46.97±12.51
TAC2	77.28±26.11	76.36±17.48	50.00±22.36	95.45±10.11	54.55±24.54	75.00±11.18	72.73±10.38	84.85±10.27	53.03±20.84

Values are presented as mean±standard deviation.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

Table 3. Measurements of the response time (second) when HLS-1 was utilized

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Male voice									
TAC1	2.11±0.78	1.47±0.15	1.80±0.25	1.71±0.31	2.24±0.50	1.97±0.36	1.74±0.24	1.63±0.17	2.09±0.37
TAC2	2.26±0.78	1.72±0.23	2.03±0.34	1.59±0.40	2.14±0.74	1.87±0.45	1.91±0.27	1.66±0.24	2.11±0.45
Female voice									
TAC1	2.14±0.74	1.96±0.40	2.05±0.96	1.86±0.40	2.19±0.99	2.02±0.66	2.02±0.47	1.92±0.40	2.14±0.83
TAC2	1.64±0.37	2.04±0.33	1.60±0.55	2.11±0.75	1.88±0.29	1.99±0.42	1.85±0.26	2.07±0.45	1.78±0.33

Values are presented as mean±standard deviation.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

(P<0.05); however, in other situations, there were no significant differences between TAC1 and TAC2 (P>0.05). In the fricative-position analysis (comparing the words that begin with fricatives [s~ and f~; front-f] and the words that end in fricatives [~s, ~f, and ~th; rear-f]), there were no significant differences between TAC1 and TAC2 for all situations in the Mann-Whitney test (P>0.05). In the fricative-type analysis (comparing the words whose fricative is s [s~ and ~s], f [f~ and ~f], and th [~th]), there were no significant differences between TAC1 and TAC2 for all situations in the Mann-Whitney test (P>0.05). Table 3 shows the response time (second) of the subjects when HLS-1 was utilized. The response time was measured as the time interval between the end of the sound file and the clicking time of the mouse to select a word on the monitor. In the fricative-position analysis, there were no significant differences between TAC1 and TAC2 for all situations (P>0.05). In the fricative-type analysis, there were no significant differences between TAC1 and TAC2 for all situations (P>0.05).

Clinical measurements when the HLS-2 was utilized

Table 4 shows the correction ratio when HLS-2 was utilized. In the fricative-position analysis, there were no significant differences between TAC1 and TAC2 for all situations (P>0.05). In the fricative-type analysis, there were no significant differences

Table 4. Measurements of the correction ratios (%) when HLS-2 was utilized

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Male voice									
TAC1	30.00±34.96	80.00±18.86	90.00±21.08	85.00±21.08	60.00±24.15	72.50±21.08	71.11±15.89	82.22±18.29	70.00±20.49
TAC2	40.00±21.08	78.00±28.98	75.00±26.35	85.00±12.91	42.50±26.48	63.75±16.08	68.89±19.46	81.11±17.41	53.33±23.31
Female voice									
TAC1	65.00±33.75	86.00±21.19	55.00±15.81	82.50±16.87	62.50±21.25	72.50±14.19	74.44±14.86	84.44±15.00	60.00±17.92
TAC2	65.00±33.75	70.00±31.62	55.00±36.89	85.00±17.48	62.50±21.25	73.75±16.08	65.56±20.59	76.67±23.69	60.00±16.10

Values are presented as mean±standard deviation.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

Table 5. Measurements of the response times (second) when HLS-2 was utilized

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Male voice									
TAC1	2.50±1.04	1.97±0.45	2.13±0.78	2.18±0.84	2.11±0.68	2.14±0.87	2.12±0.56	2.06±0.71	2.11±0.64
TAC2	2.15±0.45	2.12±0.63	2.21±0.56	2.28±1.14	2.23±0.63	2.26±0.83	2.15±0.50	2.19±0.81	2.22±0.56
Female voice									
TAC1	3.06±1.92	2.24±0.58	2.36±1.09	2.22±0.69	2.02±0.68	2.12±0.58	2.45±0.71	2.23±0.44	2.13±0.69
TAC2	2.51±0.80	2.39±0.83	2.26±1.19	2.17±0.40	2.13±0.65	2.15±0.45	2.39±0.79	2.29±0.61	2.17±0.76

Values are presented as mean±standard deviation.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

Table 6. Comparison of correction ratios between HLS-1 and HLS-2

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Mail voice									
TAC1	0.91	0.01	0.01	0.10	0.31	0.86	0.97	0.00	0.06
TAC2	0.12	0.18	0.03	0.36	0.51	0.23	0.69	0.19	0.80
Female voice									
TAC1	0.85	0.90	1.00	0.05	0.04	0.50	0.77	0.19	0.08
TAC2	0.43	0.88	0.70	0.12	0.44	0.91	0.32	0.61	0.31
Total									
TAC1	1.00	0.08	0.02	0.03	0.07	0.43	0.94	0.03	0.03
TAC2	0.71	0.76	0.04	0.22	0.91	0.37	0.83	0.52	0.57

P-values in the Mann-Whitney test.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

Table 7. Comparison of response times between HLS-1 and HLS-2

Voice	~th	~s	~f	s~	f~	front-f	rear-f	fri-s	fri-f
Mail voice									
TAC1	0.34	0.04	0.22	0.34	0.46	0.97	0.04	0.02	0.60
TAC2	0.97	0.31	0.46	0.03	0.50	0.28	0.34	0.02	0.38
Female voice									
TAC1	0.15	0.19	0.46	0.29	0.46	0.50	0.13	0.08	0.97
TAC2	0.00	0.42	0.08	0.40	0.86	0.38	0.04	0.38	0.22
Total									
TAC1	0.08	0.02	0.23	0.22	0.30	0.63	0.02	0.01	0.68
TAC2	0.03	0.06	0.10	0.03	0.41	0.10	0.03	0.03	0.19

P-values in the Mann-Whitney test.
HLS, hearing loss simulator; ~th, words that end in th; ~s, words that end in s; ~f, words that end in f; s~, words that begin with s; f~, words that begin with f; front-f, words that begin with fricatives; rear-f, words that end in fricatives; fri-s, words with fricative s; fri-f, words with fricative-f; TAC, testing algorithm combination.

between TAC1 and TAC2 for all situations ($P>0.05$). Table 5 shows the response times of the subjects when HLS-2 was utilized. In the fricative-position analysis, there were no significant differences between TAC1 and TAC2 for all situations ($P>0.05$). In the fricative-type analysis, there were no significant differences between TAC1 and TAC2 for all situations ($P>0.05$).

Comparison between the measurements of HLS-1 and HLS-2

Table 6 represents the comparison of correction ratios between HLS-1 and HLS-2. There were significant differences between the results of HLS-1 and HLS-2 for (~s, male voice, TAC1), (~f, male voice, TAC1), (~f, male voice, TAC2), (~f, total, TAC1), (~f, total, TAC2), (s~, total, TAC1), (f~, female voice, TAC1), (fri-s, male voice, TAC1), (fri-s, total, TAC1), and (fri-f, total, TAC1) ($P>0.05$). Table 7 represents the comparison of response times between HLS-1 and HLS-2. There were significant differences between the results of HLS-1 and HLS-2 for (~th, female voice, TAC2), (~th, total, TAC2), (~s, male voice, TAC1), (~s, total, TAC1), (s~, male voice, TAC2), (s~, total, TAC2), (rear-f, male voice, TAC1), (rear-f, female voice, TAC2), (rear-f, total, TAC1), (rear-f, total, TAC2), (fri-s, male voice, TAC1), (fri-s, male voice, TAC2), (fri-s, total, TAC1), and (fri-s, total, TAC2) ($P>0.05$).

DISCUSSION

The purpose of this study is not to show whether dichotic hearing can improve speech intelligibility of the HI person or not because the clinical benefits of dichotic hearing on speech intelligibility are currently on debate as mentioned above. Rather, the purpose of this study is to see whether the simultaneous application of the nonlinear frequency compression and dichotic hearing—which are expected to provide a synergetic effect considering the concept of the individual techniques—would induce a synergetic effect and improve speech intelligibility compared to the sole application of the nonlinear frequency compression.

In this study, the clinical tests were not performed with actual HI patients with severe hearing loss in high-frequency ranges, but with NH subjects and an HLS that had parameters configured for severe hearing loss in high-frequency ranges. There have been several previous reports that utilized a device that simulates various hearing-impairment conditions for clinical tests. For example, Loebach and Pisoni [22] performed a clinical test using 155 NH subjects and a cochlear implant simulator (eight-channel sinewave vocoder) to evaluate the clinical efficacy of training. Kagomiya and Nakagawa [23] evaluated the performance of hearing assistance devices using nine NH Japanese subjects and a cochlear implant simulator. Nejime and Moore [24] investigated the effect of digital processing, which slows the speed of speech without changing its pitch, using young, NH, native English speakers and a cochlear hearing loss simulator. The benefits of using a hearing loss simulator are remarkable because accurate HI subject recruitment for a specific study is extremely difficult, for example, when the testing stimuli are composed of a language foreign to the subject.

In this study, two types of simulator (HLS-1 or HLS-2) were utilized. Among the two utilized simulators, HLS-2 is more realistic because the deterioration of the frequency selectivity and abnormal hearing thresholds occur simultaneously in almost all sensorineural HI persons. In a clinical viewpoint, HLS-1 does not reflect the actual hearing impairment cases. However, there have been several studies that utilized a simulator that can only adjust the hearing threshold [11,22,23] and therefore, in this study, we performed the clinical test using both simulators.

In fact, before comparing the TAC-1 and TAC-2, as a preliminary test to see the effect of the nonlinear frequency compression in the utilized experimental setting, we performed additional comparison test using two algorithm combinations for each of HLS-1 and HLS-2: (1) original sound→WDRC→HLS →NH subject (TAC0) and (2) original sound→nonlinear frequency compression→WDRC→HLS→NH subject (TAC1). In this comparison study, the average correction scores (for all types and positions of the fricatives and all voice genders) of the TAC0 and TAC1 were 19.7 and 24.3 (among 34 testing words) for HLS-1 and 27.0 and 24.7 for HLS-2. Since the non-linear frequency compression can worsen the spectral selectivity in high-frequency regions while it can make the high-frequency sounds audible, it may improve the recognition of fricatives in HLS-1 because the HLS-1 maintains the high spectral selectivity of the NH listeners; in contrast, in case of the HLS-2, both of the nonlinear frequency compression and the HLS-2 (which also simulates spectral smearing effect) worsen the spectral selectivity simultaneously and as a result, the recognition of fricatives would be worse. Taking these points into consideration, it can be concluded that both of the utilized simulators worked properly.

Experimental results of this simulation study demonstrated that the sole application of either HLS-1 or HLS-2 cannot induce the synergetic effect of improving the speech intelligibility of HI persons compared to the application of the nonlinear frequency compression technique only. There may be several possible reasons for these results: first, the utilized simulators cannot emulate the characteristics of real HI patients sufficiently since there are several other characteristic phenomena of HI persons, such as loudness recruitment, that the utilized simulators do not reflect; and secondly, the numbers of subjects and tested words are not sufficient for reliable statistical investigation. In addition, the effect of dichotic hearing on speech intelligibility improvement is still debatable, though it is generally regarded that dichotic hearing can decrease the spectral masking thresholds of an HI person. For example, Chaudhari and Pandey [25] reported that when they performed speech perception tests for vowel-consonant-vowel (VCV) and consonant-vowel (CV) words using 10 HI subjects and 18 filter banks, which were divided into odd bands and even bands, employing dichotic hearing improved the recognition score and reduced the response time for both VCV and CV words. In contrast, Murase et al. [26] reported that when they played a recording of VCV and CV syllables for four HI subjects in four different ways (diotic, diotic with amplitude –6 dB, dichotic with cross-over frequency 0.8 kHz, and dichotic with cross-over frequency 1.6 kHz) the rank of speech recognition score was dichotic (0.8 kHz)>diotic>diotic (–6 dB)>dichotic (1.6 kHz). Mani et al. [27] reported that when they played a recording of 30 sentences for eight bilateral nucleus-24 implant users in three different ways (diotic, low-high dichotic, and odd-even dichotic) the rank of speech recognition score was diotic>odd-even dichotic>low-high dichotic. Furthermore, Kolte and Chaudhari [28] reported that when they played a recording of VCV words processed by an 18-band dichotic comb filter to seven HI subjects, the speech perception score increased for four subjects but decreased for three subjects. In addition, the response time decreased for five subjects but increased for two subjects. As shown in these previous reports, dichotic hearing improved speech recognition in some studies, but other studies that showed that dichotic hearing did not improve speech recognition.

When evaluating the clinical effects of a specific speech enhancement algorithm using NH subjects and a simulator that emulates various hearing loss conditions, the performance and characteristics of the utilized simulator can seriously affect the experimental results. For example, in this study, we selected two HLSs with different characteristics that were commonly utilized in other studies: HLS-1 reflected hearing threshold variations only and HLS-2 reflected both hearing threshold variations and the spectral smearing effect simultaneously. Although there were no statistically significant differences between the experimental results of TAC1 and TAC2 in most testing conditions when either HLS-1 (3.1) or HLS-2 (3.2) was applied, there were significant differences between the results of HLS-1 and HLS-2 at several testing conditions (3.3), which may have been due to the difference between the two utilized simulators. These experimental results may be explained as follows. There are several factors that affect the speech intelligibility of the listener such as temporal and spectral selectivity, temporal and spectral masking, level of hearing thresholds, binaural summation, loudness recruitment, right ear advantage, and so on. However, the specific role of each of those factors is not clear; (1) one factor can affect the recognition of a specific sound independently, (2) two or more factors can affect the recognition of a specific sound complexly, and (3) one factor can affect the recognition of sounds more dominantly than other factors. Considering the experimental results of this study, it may be postulated that the effect of the deteriorated hearing thresholds may be the most dominant factor for speech recognition of HI person, and that the spectral selectivity of the ear may also affect the recognition of the fricative s and f critically. Though the evidence is not sufficient for any solid conclusions and more specified and well-designed investigations should be conducted, the result of this study can be a starting point for such further clinical investigations.

In future studies, the reliability of the results of the current study can be improved by (1) recruiting more subjects and testing words, and (2) utilizing a more updated simulator for hearing loss simulation that can reflect various acoustic characteristics of actual HI persons, e.g., loudness recruitment and right ear advantage.

In conclusion, simultaneous application of the nonlinear frequency compression and dichotic hearing techniques did not significantly improve the recognition of words with fricatives compared to the sole application of nonlinear frequency compression in a severe hearing loss setting. Although it is generally accepted that dichotic hearing can decrease the spectral masking thresholds of an HI person, further verification of its clinical benefit on speech intelligibility is required.

CONFLICT OF INTEREST

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

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