Temporal and Directional Cue Effects on the Cocktail Party Problem for Patients With Listening Difficulties Without Clinical Hearing Loss

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Objectives: To evaluate the listening difficulty in a cocktail party environment in the sound field in order to better demonstrate patients' difficulties listening in noise, and to examine temporal and directional cue effects on the speech intelligibility in patients with listening difficulties in noise in comparison with control subjects.

Design: This study examined and analyzed 16 control subjects without any complaints of listening difficulties and 16 patients who had visited the outpatient clinic of the Department of Otolaryngology-Head and Neck Surgery, Tohoku University Hospital, with complaints of listening difficulties, especially in background crowded conditions, despite having relatively good hearing on routine audiograms and speech audiometry. Using five loudspeakers located in front of the subject and at 30° and 60° to the left and right from the front, word intelligibility for the target voice (female talker) presented from one of the loudspeakers in random order with four distractor voices (male talker) was assessed under the following cue conditions: (1) "no additional temporal/directional cue (only talker sex as a cue)"; (2) "fixed temporal cue without directional cue" (white noise bursts [cue sounds] were presented from the five loudspeakers just before word presentation at 500-ms intervals); (3) "directional + variable temporal cues" [cue sounds were presented from the loudspeaker where the next target word would be presented with a variable inter-stimulus interval [ISI] of 500, 1000, 1500, or 2000 ms between the cue sound and word presentation); and (4) "directional + fixed temporal cues" (cue sounds were presented from the loudspeaker where the next target word would be presented with a fixed ISI of 500 ms).

Results: The results indicated the following: (1) word intelligibility under distractors was significantly deteriorated in patients with listening difficulties compared with control subjects, although the clinical speech in noise test using the headphone system did not show any significant differences between the two groups; (2) word intelligibility under distractors for patients with listening difficulties was significantly improved with directional cues presented in advance; and (3) under most cue conditions, individual differences in word intelligibility among patients with listening difficulties were significantly correlated with their dichotic listening ability, which is one of the indicators used to assess auditory selective attention ability.

Conclusions: The results of this study indicate the usefulness of the presentation of directional cues for speech comprehension in the cocktail party situation in patients with listening difficulties, as well as the importance of evaluating the degree of listening difficulties spatially in the cocktail party situation.

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INTRODUCTION

Patients with sensorineural hearing loss often complain of difficulties in speech perception in a noisy environment. However, individuals without clinical hearing loss sometimes also complain of similar listening difficulties. That is, in most of these individuals, "one-to-one" conversations are usually possible without any problem, but they also often experience listening difficulties in relatively complicated situations, such as those with background noise or crowded environments in which many people are talking. These types of listening difficulties can occur in a variety of peripheral and central pathologies (Edwards 2020; Dillon and Cameron 2021). For example, hidden hearing loss due to cochlear synaptopathy, which is caused by cochlear neural and/or synaptic pathology without hair cell damage, is one of the possible peripheral pathologies that causes listening difficulties in the presence of background noise with normal hearing thresholds (Kujawa and Liberman 2009; Schaette and McAlpine 2011; Liberman 2015, Liberman et al. 2016; Liberman and Kujawa 2017). However, even when no such pathology appears to be present in the periphery, any pathology in the central processing systems related to speech perception and cognition could also be involved as a possible causal factor for the listening difficulties (Dawes and Bishop 2009; American Academy of Audiology 2010; British Society of Audiology 2011; Moore 2011, 2018, Sharma et al. 2014; Tomlin et al. 2015; Obuchi et al. 2017; Dillon and Cameron 2021). That is, it is thought that not only problems in the auditory processing system in the narrow sense, but also problems in the relevant supporting systems needed for auditory, speech, and/or language processing, such as attention, working-memory, and top-down information processing, could cause the listening difficulties (Dawes and Bishop 2009; American Academy of Audiology 2010; British Society of Audiology 2011; Moore 2011, 2018, Sharma et al. 2014; Tomlin et al. 2015; Obuchi et al. 2017; Dillon and Cameron 2021).

Such patients with listening difficulties due to possible central processing issues basically show no abnormalities in routine audiological tests including audiometry, speech audiometry, auditory brainstem response (ABR), and otoacoustic emission (OAE). To diagnose these patients' listening difficulties, it has been shown to be important that poor performance in a variety of tests conducted to evaluate the central auditory processing system, such as the gaps-in noise test, dichotic listening test,

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and low redundancy speech perception tests, such as perception for time compression speech signals and speech in background noise or verbal competition (American Academy of Audiology 2010; Ahmmed et al. 2014). Of these tests, the evaluation of listening comprehension in the presence of disturbing sounds has an aspect as an objective visualization of the degree of difficulties in speech perception in a noisy environment, which is a typical complaint of patients. However, we have often found that the results of the speech in noise test with a headphone system, which is routinely performed in our ENT outpatient clinic, did not reveal the degraded performance for people with self-reported listening difficulties (Musiek and Baran 2002; American Academy of Audiology 2010).

The ability to listen to a particular sound in a background with many distractor sounds is known as the "cocktail party effect" (Cherry 1953; Yost 1997; Bronkhorst 2000, 2015). Considering that listening problems in everyday life, where spatial hearing plays an important role, were the main complaint of patients complaining of listening difficulties, it might be reasonable to assess the degree of listening difficulties observed in patients with normal hearing from the viewpoint of the cocktail party problem.

Therefore, we thought that there might be a limitation in using a headphone system to evaluate the listening problem because spatial hearing plays an important role in daily life, and speech intelligibility in noise was assessed using a spatially set loudspeaker system on a trial basis in one patient with listening difficulties, expecting better visualization of a patient's complaint of listening difficulties in a noisy situation (Kawase et al. 2019). That particular patient showed an apparent abnormality in auditory detection, as measured with the auditory attention task in the "Clinical Assessment for Attention" test battery, which was developed by the Japan Society of Higher Brain Dysfunction (Japan Society for Higher Brain Dysfunction 2006; Takeda et al. 2011). The patient showed no apparent abnormalities in other audiological tests, including the dichotic listening test and the speech in noise test with a headphone system. Since we were conducting a study of the effect of attentional cues on cocktail party listening for normal subjects using the loudspeaker system as another research project at that time (Fujimura et al. 2018), the listening ability in distracting sounds of this patient was first exploratorily examined using this system. The results of this exploratory measurement showed that word intelligibility under the distractors of this patient was apparently worse compared to normal subjects, but it improved markedly to almost the same level as that of normal subjects when attentional cues were presented in advance (Kawase et al. 2019). That is, the result obtained from this particular patient hint that the evaluation of listening difficulty in a cocktail party environment in the sound field may better demonstrate patients' difficulties listening in noise, and that the presentation of attentional cues may significantly contribute to improving listening comprehension in patients with listening difficulties.

Although the detailed mechanisms underlying the cocktail party effect have not been fully clarified, the following two mechanisms are thought to play a major role in signal perception in the presence of noise: the signal segregation process represented by "auditory scene analysis" and the "selective attention" mechanism to maintain attention on the signal to be heard (Cherry 1953; Bregman 1990; Yost 1997; Carlyon 2004). Difficulties with either process could cause listening difficulties in the presence of noise.

As for the relationship between auditory selective attention and speech intelligibility in the cocktail party listening task, individual selective attention ability is known to affect listening ability in the presence of noise, even in healthy subjects with no subjective complaints of such listening difficulties. That is, individual differences in selective attention could be a contributing factor to individual differences in listening ability in the presence of noise within normal audiometric thresholds (Oberfeld and Klöckner-Nowotny 2016). This suggests that inadequate attentional mechanisms such as fluctuating attention levels, inattention tendencies, and deficits in sustained and divided attention, which are often pointed out in patients with listening difficulties (Sharma et al. 2014; Gyldenkærne et al. 2014; Roebuck and Barry 2018; Stavrinos et al. 2018), may be among the factors that cause listening difficulties under a cocktail party environment in such patients, in addition to the possible impaired ability of scene analysis (Lotfi et al. 2016).

If such is the case, it would be expected that speech intelligibility in the presence of noise for patients with listening difficulties might be improved by strategies to strengthen auditory selective attention. One possible way to enhance auditory selective attention and facilitate the cocktail party effect is "cue" presentation. The mechanism of "auditory selective attention" consists of several domains, such as pitch, spatial, and temporal, and it is known that spatial, temporal, and/or frequency cues related to signals, which are presented in advance, facilitate the cocktail party effect (Ebata 2003; Bronkhorst 2000, 2015; Greenberg and Larkin 1968; Scharf et al. 1987; Schlauch and Hafter 1991; Arbogast and Kidd 2000; Kidd et al. 2005; Wright and Fitzgerald 2004; Teraoka et al. 2021). It has been indicated that the spatial separation of the speech signal from a distractor is one of the most important factors, and that spatial information related to the target stimuli improves performance in a range from several to >10 dB; that is, spatial attention to a particular direction improves perception of the target sounds presented from that direction compared with those presented from other directions, and in the case that the direction of the target sound presentation changes randomly, the perception of the target sound is improved when cues are presented in advance as to from which direction the target will be presented (Ebata 2003; Bronkhorst 2000, 2015; Scharf et al. 1987; Arbogast and Kidd 2000; Kidd et al. 2005; Teraoka et al. 2021).

On the other hand, the effect of temporal cues on when the target is presented is generally much smaller than the magnitude of the cueing effects of a spatial cue (Wright and Fitzgerald 2004; Holmes et al. 2018; Teraoka et al. 2020).

To date, these cueing effects have not been examined for subjects with subjective listening difficulties but normal audiometric thresholds; thus, the cue effects for patients with listening difficulties have not been clarified. However, considering the possible involvement of attention problems in such patients, it may be important to clarify whether the effects of cue presentation on the cocktail party effect may be limited due to problems in the auditory processing system, including the attention system, or be considerably good by allowing the patient to be able to take advantage of the attention reinforcement effect of the cue, as hinted by the results of our exploratory measurement described above.

Given this background, in the present study, word intelligibility for targets in distractors was evaluated in a cocktail party environment in the sound field for patients with listening difficulties and a control group with no difficulties. The effects of temporal and spatial cues were examined to determine the effectiveness of these cues in speech perception in patients with listening difficulties.

MATERIALS AND METHODS

Subjects

This study examined and analyzed 16 healthy control subjects without complaints of listening difficulties (6 men, 10 women; mean age, 23.4 years; age range, 21 to 29 years) and 16 patients (6 men, 10 women; mean age, 21.4 years; age range, 16 to 29 years) who had visited the outpatient clinic of the Department of Otolaryngology-Head and Neck Surgery, Tohoku University Hospital, with complaints of listening difficulties in daily life, especially in crowded background conditions. All patients were referred from their previous doctors to our hospital for the purpose of a detailed examination of their difficulties in listening.

Patients with real-life listening difficulties had their difficulties confirmed by an interview with the researcher [T.K.; including a translated Japanese version of Fisher's auditory problems checklist by Obuchi and/or a questionnaire on listening difficulties developed by Obuchi and Kaga (American Academy of Audiology, 2010; Obuchi and Kaga 2020)] and had no apparent clinical hearing loss on pure tone audiograms, speech audiograms, ABR, or OAE measures. However, patients aged less than 15 years were excluded from the study in consideration of the contents of the present examination, which included familiarity with the word materials used in the study. Moreover, cases with a history of possible chronic and/or loud noise exposure and those for whom the onset of listening difficulties was in the 30s or later were also excluded to avoid the possible involvement of hidden hearing loss due to cochlear synaptopathy as much as possible. Basic patient characteristics are shown in Table 1. All patients underwent a dichotic listening test, speech in noise test, gap detection test, and Clinical Assessment for Attention test battery, which was developed by the Japan Society of Higher Brain Dysfunction (Japan Society for Higher Brain Dysfunction 2006; Takeda et al. 2011) and had been clinically diagnosed as having "listening difficulties" or "suspected listening difficulties". Although the results of these tests varied widely between subjects, the severity of the findings was not used as a reason for exclusion as long as the patient presented with listening difficulties in daily life.

Control subjects without complaints of listening difficulties were recruited from undergraduate and graduate students enrolled at four nearby universities. The absence of listening difficulties was confirmed through an interview with the researcher (T.K.) using a 5-point rating scale ("very difficult", "somewhat difficult", "undecided", "hardly any difficulty", "no difficulty at all") for listening difficulties in everyday life, including in noisy situations. In the actual interview, they were asked the following: "In your daily life including noisy situations, such as in a noisy bar and/or in a noisy classroom, do you think you have difficulties in listening (compared to other people)?", or "In such situations, do you find that you are the only one who cannot hear the conversation when others can?". Fifteen of the 16 participants chose "no difficulty at all" and one chose "hardly any difficulty". For the subjects in the control group, after confirming that there were no obvious abnormalities in the audiogram and speech audiogram (in quiet), the same dichotic listening and speech in noise tests conducted on the patients with listening difficulties were also conducted to assess individual basic audiological features under more complicated listening conditions.

Concerning the background audiological features of both groups (control and listening difficulties), the results of pure tone audiograms, speech audiometry in quiet (maximum speech intelligibility), dichotic listening, and speech in noise tests are shown in Figs. 1, 2. A "speech in noise" test was conducted using a commercially available audiometer (AA-HA; RION Co, Ltd, Kokubunji, Tokyo, Japan) with headphones (AD-02T; RION Co, Ltd). Speech intelligibility was assessed for 50 Japanese monosyllables presented at 74 dB SPL in background continuous speech noise at 73 dB SPL [signal to noise ratio (S/N) = 1 dB] and 78 dB SPL (S/N = –4 dB). The average speech intelligibility obtained from the right and left ears was evaluated as the

TABLE 1. Background characteristics of the patients with listening difficulties in the present study

Case	Age (at Exam, years)	Sex	First Awareness of Listening Difficulties in Noise	Special Note
1	20	F	Senior high school	Wireless Communication Device user (since 18 years old, only at class)
2	22	F	College	*
3	16	F	Elementary school	ASD
4	23	F	Elementary school	*
5	29	M	After work	Working memory problem
6	26	M	Elementary school	ASD
7	20	F	College	*
8	26	M	After work	ADHD
9	20	F	Elementary school	PH of suspected DD
10	25	M	After work	*
11	18	F	Senior high school	PH of suspected DD
12	22	F	After work	*
13	16	F	Junior high school	ASD
14	16	F	Elementary school	*
15	23	M	College	ASD, ADHD
16	20	F	After work	PH of temporal lobe epilepsy (only one episode at her 16 years old)

*No information.

ADHD, attention-deficit hyperactivity disorder; ASD, autism spectrum disorder; DD, developmental disorder; PH, past history.

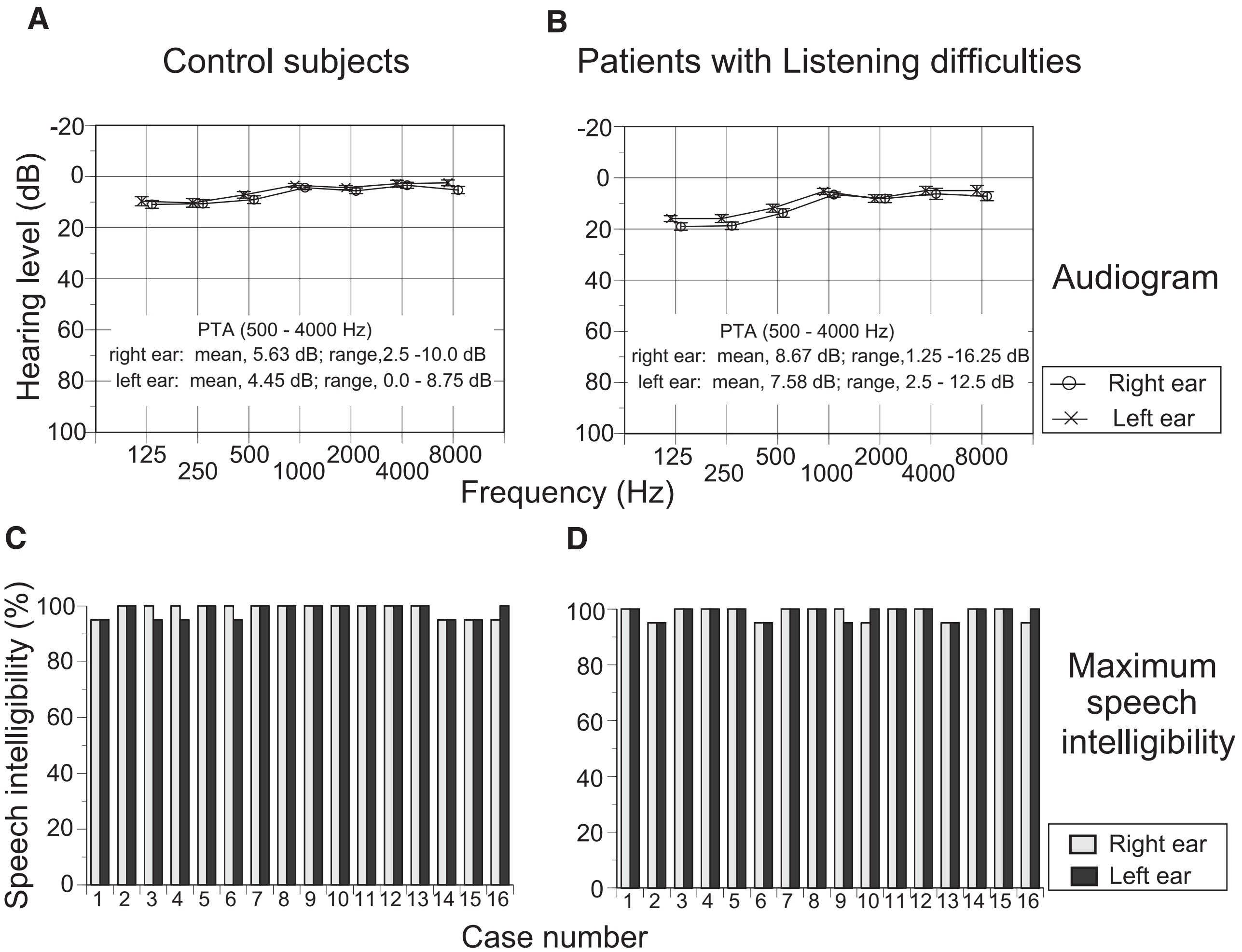

Fig. 1. Averaged audiograms and speech intelligibility for the participants. A and B, Averaged audiograms [mean ± standard error (SE)] in control subjects (A) and in patients with listening difficulties (B); C and D, Maximum speech intelligibility for 20 Japanese mono syllables (67-s word lists, Japan Audiological Society) in control subjects (C) and in patients with listening difficulties (D).

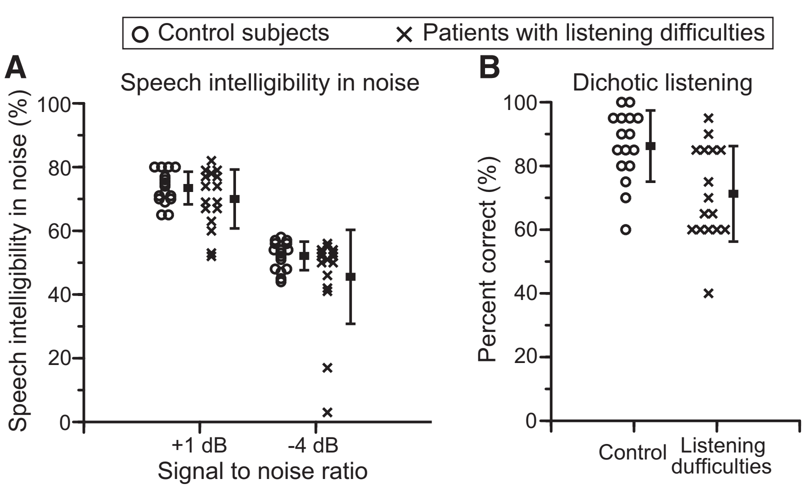

Fig. 2. Results of a speech intelligibility in noise test (A) and a dichotic listening test (B) in control subjects and patients with listening difficulties. Thick and thin bars indicate mean and ± 1 standard deviation values, respectively.

representative value for each case and is presented in Figure 2. Dichotic listening (separation) was assessed using 20 four-mora words adopted from the Familiarity-controlled Word Lists 2007 (FW07) (Kondo et al. 2008; Speech Resource Consortium). A pair of two four-mora words was presented binaurally (dichotic) at the same time using a headphone system, and the subjects were instructed to listen and distinguish the words presented in their right and left ears, paying separate attention to each ear. Each pair of test words was presented four times, and the percentage of correct answers was assessed.

This study was approved by the ethics committees of the Tohoku University Graduate School of Medicine (#2017-1-308) and the Research Institute of Electrical Communication (#2016-4, #2017-5), and written informed consent was obtained from each subject in accordance with the requirements of the ethical committee. All aspects of the study were performed in accordance with the guidelines of the Declaration of Helsinki.

Apparatus and Stimuli

The experiment was conducted in a soundproof anechoic room at the Research Institute of Electrical Communication, Tohoku University. The sound stimuli were presented through five loudspeakers, distributed from –60° to +60° (positive and negative values indicate the right and left side of the subject, respectively) with 30° separations at a distance of 1.6 m from the subject (Fig. 3A). Sound stimuli were generated using MATLAB (version 2018a; MathWorks, Natick, MA, USA) with an open-source audio I/O library (Playrec, http://www.playrec.co.uk/) on a workstation computer (Dell Precision T7910, Dell, Round Rock, TX, USA) through a MADI interface (RME MADIface USB, Synthax Japan, Obuse, Japan) and a D/A converter (ANDIAMO 2.DA, DirectOut Technologies, Tac system, Tokyo, Japan). The target sound was presented from only one of the five loudspeakers, whereas the distractors were presented from the other four. The target and distractor sounds, which were extracted from the Familiarity-controlled Word Lists 2003 (FW03) (Amano et al. 2003, Speech Resource Consortium), were composed of four-mora Japanese words uttered by female and male talkers, respectively. One thousand words ranked as having the highest level of familiarity were selected from these lists. From these words, the target speech sounds were selected from the words adopted in the FW07 (Kondo et al. 2008; Speech Resource Consortium), which is a compressed version of the FW03 for clinical use (in the FW03, one list is composed of 50 words, but in the FW07, each list is limited to 20 words to reduce the subjects' burden). The total number of target words was 400 (20 lists, 20 words per list). The other 600 words were used as distractors. In this study, one female (fhi) and one male (mya) voice were assigned as the target and distractor, respectively. The amplitudes of the target and distractor utterances were adjusted such that the equivalent continuous A-weighted sound pressure level for the target and distractors were 65 dB at the position corresponding to the center of the subject's head in the absence of the subject.

Procedure

In this study, to assess the effects of temporal and directional cues on word intelligibility, four protocols with different cue conditions— "no additional temporal/directional cue (i.e., no additional cue beyond the talker sex cue)", "fixed temporal cue without directional cue", "directional + variable temporal cues", and "directional + fixed temporal cues"— were executed for each subject (Fig. 3B–E). To examine whether the results would be different if the timing of the directional cue presentation was constant or random, the "directional + variable temporal cues" condition was examined in addition to the "directional + fixed cues" condition. The order of these four conditions was adjusted to counterbalance the order effect among the subjects. In all sessions, the subjects were instructed to focus on the target voice (i.e., the female voice) and write down the uttered words they had heard on a response sheet.

Under the "no additional temporal/directional cue" condition (Fig. 3B), one target word, uttered by the female talker, was presented from one of the five loudspeakers, with four distractors uttered by a male talker presented from the four other loudspeakers. In one test session, 100 trials were performed at 5000-ms intervals. The target words were presented through each loudspeaker in random order, but the total number of presentations was counterbalanced among all five loudspeakers (i.e., 20 words for each loudspeaker). The heads of the subjects were not restrained, but the subjects were asked to keep their head stationary and face straight ahead at 0° during the entire session.

Under the "fixed temporal cue without directional cue", "directional + variable temporal cues", and "directional + fixed temporal cues" conditions, basically the same listening tasks as those performed under the above-mentioned "no additional temporal/directional cue" condition were executed, except for the cue presentation. Under the "fixed temporal cue without directional cue" condition, as shown in Figure 3C, white noise bursts (cue sound) with a duration of 500 ms (rise–fall 50 ms) were presented from all five loudspeakers just before word presentation, with 500-ms intervals (inter-stimulus intervals [ISIs]) between the white noise bursts and word presentations. The subject was instructed in advance that the test words would be presented after a certain constant period of time from the noise presentation. Under the "directional + variable temporal cues" (Fig. 3D) condition, white noise bursts (cue sounds) were presented from the loudspeaker where the next target word would be presented with a variable ISI between the white noise bursts and word presentation. The ISI was varied randomly among 500, 1000, 1500, or 2000 ms. On the other hand, under the "directional + fixed temporal cues" condition (Fig. 3E), the cue sounds were presented from the loudspeaker where the next target word would be presented with a fixed ISI of 500 ms. Under the "directional + variable temporal cues" and "directional + fixed temporal cues" conditions, the subject was instructed in advance that the test words would be presented from the loudspeaker where the cue was presented after a varied period of time and a certain constant period of time from the noise presentation, respectively. The subjects were also asked to direct their attention to the loudspeaker from which the cue sound was presented while keeping their head stationary and facing straight ahead at 0° during the entire session.

Under each cue condition, 100 target words (five lists of 20 words) were randomly selected from the preselected 400 target words; that is, a different set of five lists was used for each of the four conditions, and each of the five lists was assigned to each of the five loudspeakers separately. Thus, there were no duplicates in the presented target words. For each cue condition, 400 distractors were randomly selected from the same 600 words, that is, there were no duplicates within each cue condition, but the same distractor words were included between different cue conditions.

Statistics

Two-way repeated-measures analysis of variance (ANOVA) with post hoc analyses Bonferroni-corrected for

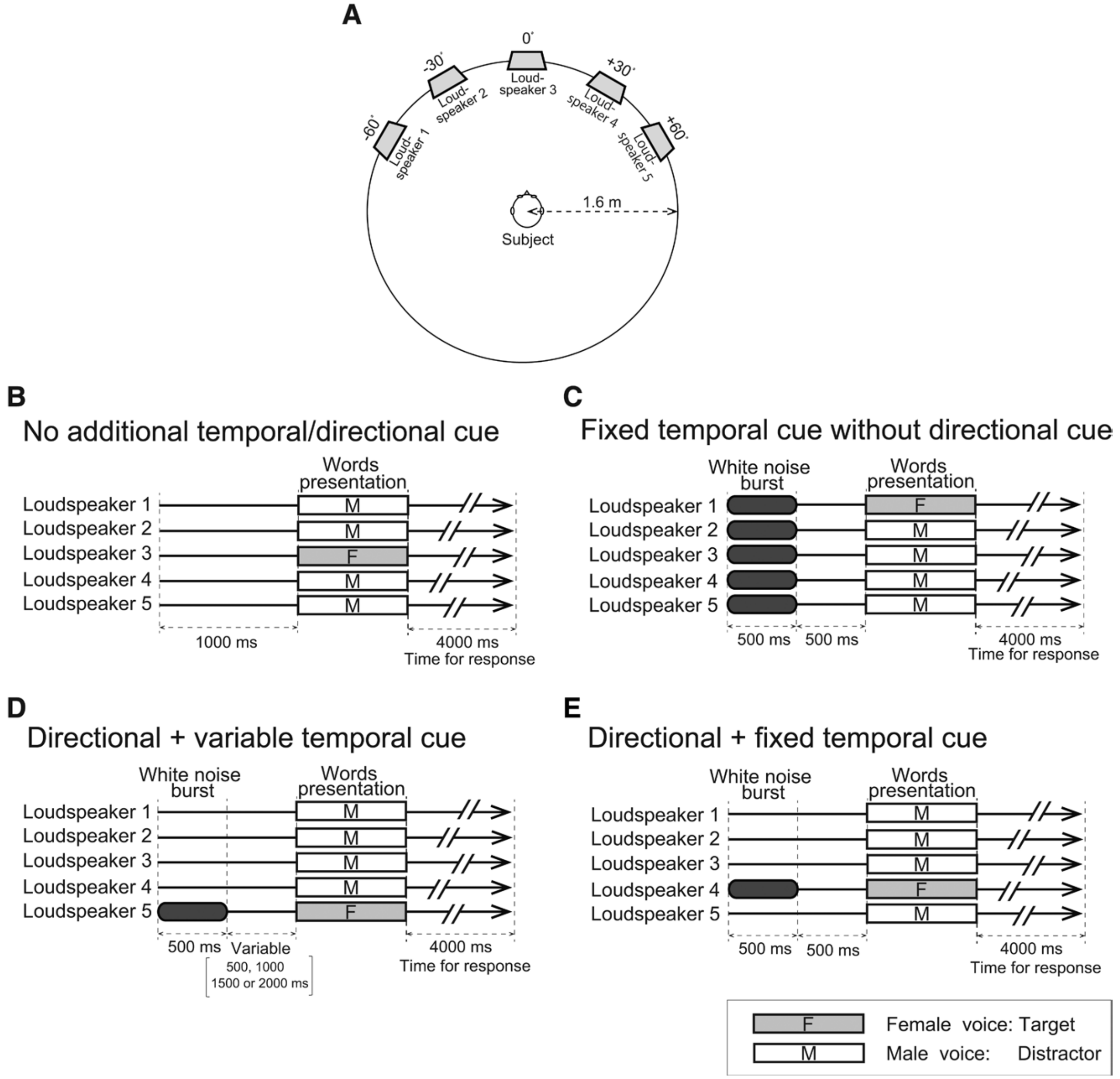

Fig. 3. Equipment and experimental protocols for measuring "word intelligibility in background distractors". A, Schematic of the loudspeaker system used in the present study; B–E, Schematic drawing of the four protocols; B, No additional temporal/directional cue condition: the target word, uttered by the female talker, is presented from one of five loudspeakers, with four distractor sounds uttered by a male talker. A total of 100 trials was performed at 5000-ms intervals. The target words are presented through the loudspeakers in random order, but the total number of presentations is counterbalanced among all five loudspeakers; C, Fixed temporal cue without directional cue condition: white noise bursts (cue sound) with a duration of 500 ms (rise–fall 50 ms) are presented from the five loudspeakers just before the words, with 500-ms intervals; D, Directional + variable temporal cues condition: white noise bursts (cue sound) are presented from the loudspeaker where the next target word would be presented. The ISI was randomly varied between 500, 1000, 1500, or 2000 ms; E, Directional + fixed temporal cues condition: Temporal + directional cues condition: white noise bursts (cue sound) are presented from the loudspeaker where the next target word would be presented, with a fixed ISI of 500 ms (see the text for the further details). ISI indicates inter-stimulus interval.

multiple comparisons was performed to test the effects of group (between-subject factor) and cue condition (within-subject factor) on the word intelligibility using SPSS ver. 26 software (IBM Corp., Armonk, NY, USA). Values of $p < 0.05$ were considered significant. The Greenhouse–Geisser correction (Geisser and Greenhouse 1958) was used if Mauchly's test of sphericity (Mauchly 1940) indicated that the assumption of sphericity was violated. Linear correlations between two sets of data (Pearson's correlation coefficient) were also assessed using SPSS. Correction for the false discovery rate was used to examine the significance of multiple linear correlations (Glickman et al. 2014). Comparisons of the slope and intercepts of two regression lines were assessed based on analysis of covariance (ANCOVA) (Tango and Furukawa 2013; McDonald 2014).

The results of basic auditory function tests, including pure tone audiometry, maximum speech intelligibility, speech intelligibility in noise, and dichotic listening (Figs. 1, 2), were also compared between the control and patient groups by two-way repeated-ANOVA or Student *t* test using SPSS.

RESULTS

Basic Audiological Background of the Participants

Averaged audiograms and speech intelligibility for the participants are shown in Fig. 1. Figures 1A–D represent averaged audiograms of the control group, those in the patient group with listening difficulties, maximum speech intelligibility in the control group and those in the patient group with listening difficulties, respectively. Differences in the pure tone average (PTA) assessed by two-way repeated-measures ANOVA performed with a between-group factor (control subjects and patients) and a within-group factor of ear (right and left ears) showed a significant main effect for group [$F(1, 30) = 7.379$, $p < 0.05$, partial $\eta^2 = 0.197$], reflecting better PTA in the control group than in the patient group with listening difficulties, a significant main effect for ear [$F(1, 30) = 6.643$, $p < 0.05$, partial $\eta^2 = 0.181$], reflecting significantly better PTA for the left ear, and insignificant group-by-ear interaction [$F(1, 30) = 0.008$, $p = 0.930$, partial $\eta^2 = 0.000$]. Differences in maximum speech intelligibility as assessed by two-way repeated-measures ANOVA performed with a between-group factor (control subjects and patients) and a within-group factor of ear (right and left ears) showed an insignificant main effect for group [$F(1, 30) = 0.048$, $p = 0.829$, partial $\eta^2 = 0.002$], reflecting no significant differences in maximum speech intelligibility between the control group and the patient group with listening difficulties, an insignificant main effect for ear [$F(1, 30) = 0.140$, $p = 0.711$, partial $\eta^2 = 0.005$], reflecting no significant difference in speech intelligibility between the right and left ears, and an insignificant group-by-ear interaction [$F(1, 30) = 1.262$, $p = 0.270$, partial $\eta^2 = 0.040$].

Figure 2 shows the results of speech intelligibility in noise tests (Fig. 2A) and a dichotic listening test (Fig. 2B) using a headphone system for the control group, as well as the patient group with listening difficulties.

Differences in speech intelligibility in noise as assessed by two-way repeated-measures ANOVA performed with a between-group factor (control subjects and patients) and a within-group factor of signal to noise (S/N) ratio (S/N = 1 dB and S/N = –4 dB) showed an insignificant main effect for group [$F(1,30) = 2.521$, $p = 0.123$, partial $\eta^2 = 0.078$], reflecting no significant difference in speech intelligibility in noise between the control group and the patient group with listening difficulties, a significant main effect for the S/N ratio [$F(1, 30) = 521.432$, $p < 0.001$, partial $\eta^2 = 0.946$], and an insignificant group-by-S/N ratio interaction [$F(1, 30) = 0.129$, $p = 0.930$, partial $\eta^2 = 0.075$]. On the other hand, on Student *t*-test, the % correct on the dichotic listening test was significantly better in the control group than in the patient group ($p < 0.01$).

Additional Cue Effects in Control Subjects and Patients With Listening Difficulties

Word intelligibility results in control subjects and in patients with listening difficulties are shown in Figure 4. Two-way repeated-measures ANOVA was performed with a between-group factor (control subjects and patients) and a within-group factor of cue condition (“no additional temporal/directional cue”, “fixed temporal cue without directional cue”, “directional + variable temporal cues”, and “directional + fixed temporal cues”). The results showed a significant main effect for group [$F(1,30) = 59.745$, $p < 0.001$, partial $\eta^2 = 0.666$], reflecting better speech intelligibility in the control group than in the patient group with listening difficulties, a significant main effect for cue conditions [$F(2.289, 68.664) = 9.974$, $p < 0.001$, partial $\eta^2 = 0.250$], reflecting significant cue effects for speech intelligibility, and a significant group-by-cue interaction [$F(2.289, 68.664) = 3.434$, $p < 0.05$, partial $\eta^2 = 0.103$]. Post hoc analyses showed that word intelligibilities were significantly lower in the patient group with listening difficulties than in the normal group under all 4 cue conditions ($p < 0.05$) and that word intelligibilities for the “directional + variable temporal cues” and “directional + fixed temporal cues” conditions in patients with listening difficulties were significantly better compared with the “no additional temporal/directional cue” condition ($p < 0.05$). However, word intelligibilities for the “fixed temporal cue without directional cue” condition were not significantly different from those for the “no additional temporal/directional cue” condition. Furthermore, there was no significant difference in word intelligibilities among any of the four cue conditions (“no additional temporal/directional cue”, “fixed temporal cue without directional cue”, “directional + variable temporal cues”, and “directional + fixed temporal cues”) in the control group and between any of the three additional cue conditions (“fixed temporal cue without directional cue”, “directional + variable temporal cues”, and “directional + fixed temporal cues”) in the patient group.

Correlation Between Clinical Data and Word Intelligibility With/Without Additional Cues

As shown in Figure 2, the dichotic listening and speech in noise tests that were performed to assess individual basic audiological features in more complicated listening conditions indicated relatively inhomogeneous characteristics between the participants. Therefore, the impact of the individual variability of these data on word intelligibility with and without additional cues is presented in Figs. 5, 6.

The relationships between dichotic listening ability and word intelligibility under each cue condition are shown in Figure 5. Basically, positive relations tended to be obtained in both control subjects and patients with listening difficulties; that is, the better the dichotic listening ability, the better the word intelligibility obtained in the sound field. The comparison of the two regression lines for each cue condition using ANCOVA showed no significant differences in slopes between those obtained from control subjects and patients with listening difficulties for all four cue conditions. In contrast, significant differences were found between the intercepts of two regression lines obtained from control subjects and patients with listening difficulties for all four cue conditions, reflecting the overall poorer word intelligibility performance in the patient group than in the control group ($p < 0.005$ for all four cue conditions).

The relationship between speech intelligibility in the presence of noise based on clinical measurements (S/N = 1 dB condition) using headphones and word intelligibility under each cue condition is shown in Figure 6. In both groups, no significant correlation was observed between speech intelligibility in noise as measured clinically using headphones and the word intelligibility obtained in the present study.

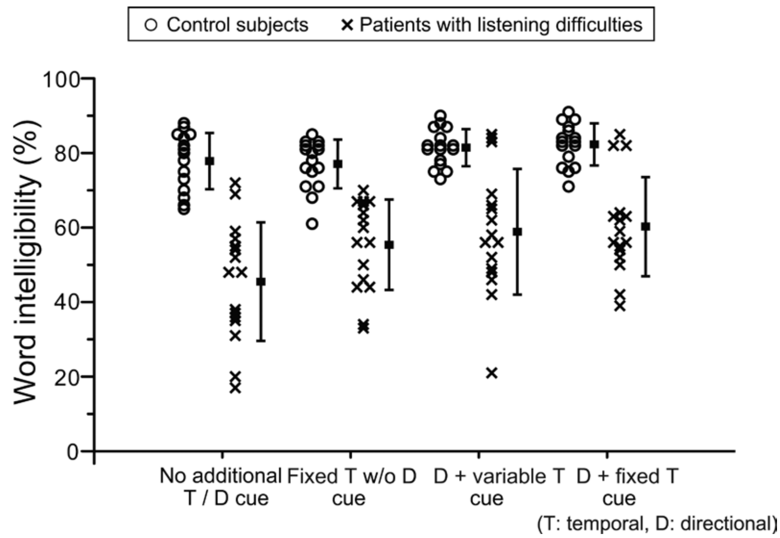

Fig. 4. Word intelligibility for four different cue conditions in control subjects (open circles) and patients with listening difficulties (crosses). Thick and thin bars indicate mean and ± 1 standard deviation values, respectively.

DISCUSSION

In this study, word intelligibility under distractors was examined in patients with listening difficulties, as well as in control subjects without listening difficulties, taking into consideration directional and temporal cues. The following results were obtained: (1) word intelligibility under distractors was significantly deteriorated in patients with listening difficulties, although their audiograms and speech intelligibility under quiet conditions were basically within the normal range, and maximum speech intelligibility in noise as assessed using a headphone system was not significantly different between patients with listening difficulties and control subjects; (2) word intelligibility under distractors was significantly improved by additional "directional cues" presented in advance; and (3) word intelligibility as measured in the present study tended to correlate with dichotic listening ability in both control subjects and patients with listening difficulties.

Additional Cue Effects in Patients With Listening Difficulties

In the present study, additional temporal and/or spatial cue effects beyond the cue of talker sex on word intelligibility under noisy conditions, namely a cocktail party situation, were examined using five loudspeakers set in a soundproof anechoic room. In the study task, subjects listened to words uttered by a female talker presented from one of the five loudspeakers and distinguished them from words spoken by male talkers presented from the other four loudspeakers. Moreover, the location from which the words were spoken by the female talker was randomized. In general, when listening to short speech signals embedded in distracting sounds, the spectro-temporal structure of the speech signal has the strongest influence on the formation of the auditory object (Bregman 1990; Darwin 1997; Shinn-Cunnngham and Best 2008), whereas other cues, such as spatial cues in signals, are thought to play only some additional role in object grouping (Drennan et al. 2003; Darwin 2006; Shinn-Cunnngham and Best 2008). However, it seems that the degree to which spatial cues can be used would be important from the viewpoint of the effective use of spatial release from masking under the test conditions in the present study (Arbogast et al. 2002; Culling et al. 2004). Therefore, under the "no additional temporal/directional cue" condition in the present study, it was presumed that the subjects would mostly use selective attention in the pitch domain to search for and distinguish the female talker's voice. Moreover, it was presumed that they would use spatial cues as much as possible while directing their spatial attention to where the target female voice was presented. In other words, it may be said that the present study examined how much the addition of temporal and/or directional cues facilitates these processes. Considering the time required to buildup selective attention (Best et al. 2018), it would be expected that spatial cues as to the direction of the target voice presented in advance may have had considerable supplemental effects on the buildup of selective attention, whereas the temporal cues presented in advance may have played a role in terms of "alerting".

The present study showed significant cue effects in patients with listening difficulties for the "directional + variable temporal cues" and "directional + fixed temporal cues" conditions compared with the "no additional temporal/directional cue" condition, but significant effects of the temporal cue could not be obtained. Moreover, no significant differences were seen between the word intelligibilities under the "directional + fixed temporal cues" condition and those under the "directional + variable temporal cues" condition, although a slightly higher percentage of correct responses (about 5%) was reported when the signals were presented under a condition with fixed compared with random timing (Wright and Fitzgerald 2004). These results seem to suggest the effectiveness of presenting a spatial cue in speech comprehension in the cocktail party situation for patients with listening difficulties regardless of the timing of the cue presentation (fixed or random).

One of the limitations of the present study is that the cue effects were examined under only one limited sound pressure condition of the signal to noise (distractors) ratio considering the patient burden. To obtain the whole picture of the cueing effects on speech comprehension in the cocktail party environment, it may be necessary to examine different S/N conditions as well. In the present study, it was not possible to observe any significant the effect of cueing in the control group, but there is a possibility

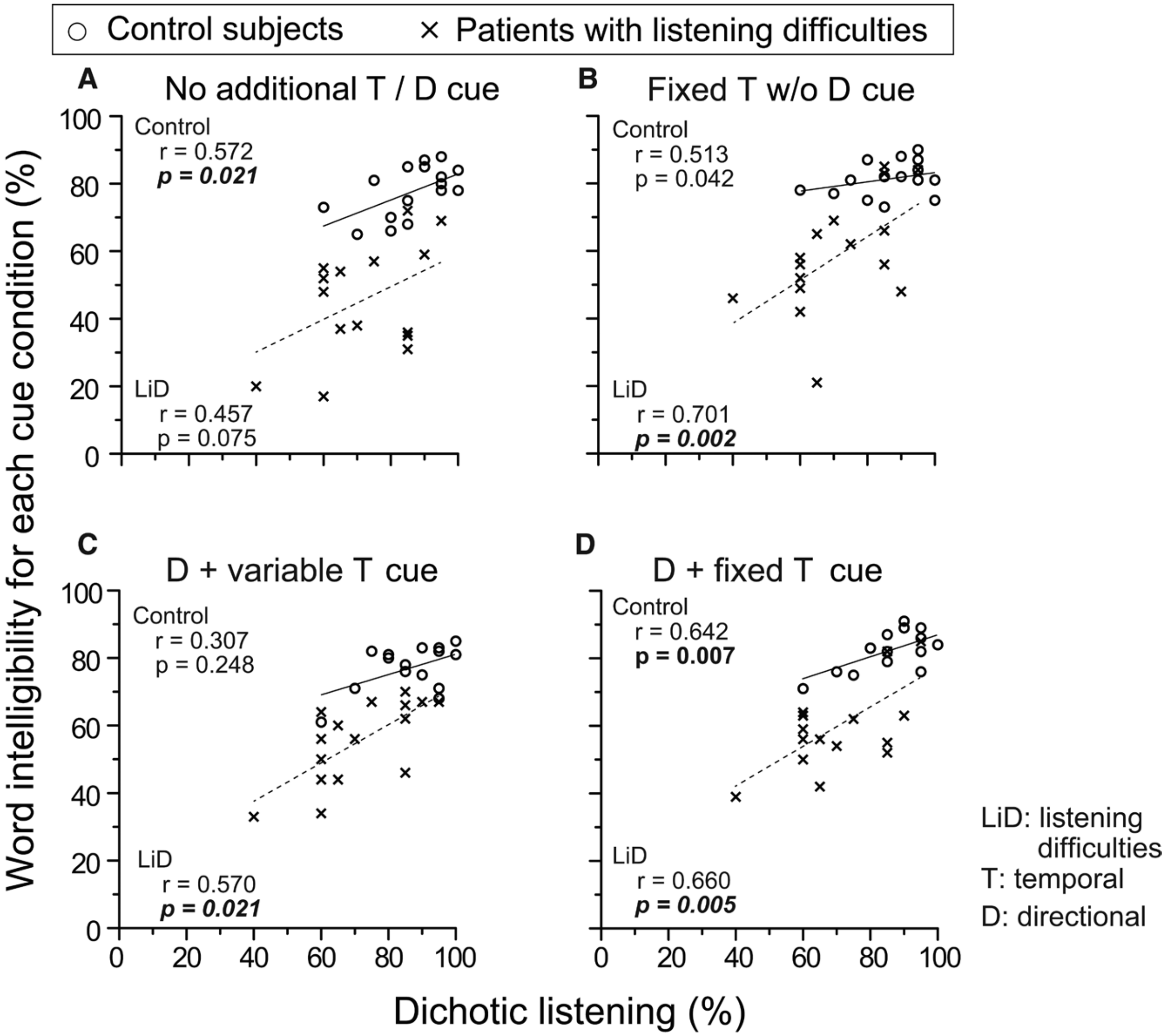

Fig. 5. Relationships between dichotic listening ability (% correct) and word intelligibility for each cue condition for all participants [control subjects (open circles) + patients with listening difficulties (crosses)]. Dotted lines in each figure indicate regression lines for the plotted data. *P* values found to be significant after FDR correction are shown in bold. FDR indicates false discovery rate.

of a ceiling effect. If the cueing effects were examined under more severe S/N conditions, a significant effect may be obtained even in the control group, as previously reported (Ebata 2003; Bronkhorst 2000 2015; Greenberg and Larkin 1968; Scharf et al. 1987; Schlauch and Hafter 1991; Arbogast and Kidd 2000; Kidd et al. 2005; Wright and Fitzgerald 2004; Teraoka et al. 2021).

From the clinical point of view, the present results concerning the considerable effectiveness of additional attentional cues for deteriorated speech intelligibility in the presence of noise reinforce the importance of "securing attention", that is, to make the listener pay attention to the talker and/or the speech signal, as stated in recommended general management strategies for patients with listening difficulties (British Society of Audiology 2011).

Comparison Between Basic Audiological Data and Word Intelligibility Obtained in the Present Study

As for the relationship between individual listening ability in noise and selective attention ability in normal hearing subjects without a history of hearing disorders, it is known that the individual differences in selective attention could be a contributing factor to individual differences in listening ability in the presence of noise (Oberfeld and Klöckner-Nowotny 2016). Abnormalities in the auditory attention system in patients with listening difficulties have been shown, but the relationship between the deterioration of speech intelligibility in the presence of noise and that of selective attention ability has not been fully investigated (Moore et al. 2010; Sharma et al. 2014; Roebuck and Barry 2018; Stavrinos et al. 2018; Gyldenkærne et al. 2014). However, the positive correlation seen between dichotic listening ability and word intelligibility in the distractor shown in Figure 5 supports the idea that individual differences in selective attention ability are among the factors that could also affect the individual differences observed in word intelligibility in patients with listening difficulties, because the dichotic listening test is one of the methods for assessing selective attention ability (Cherry 1953).

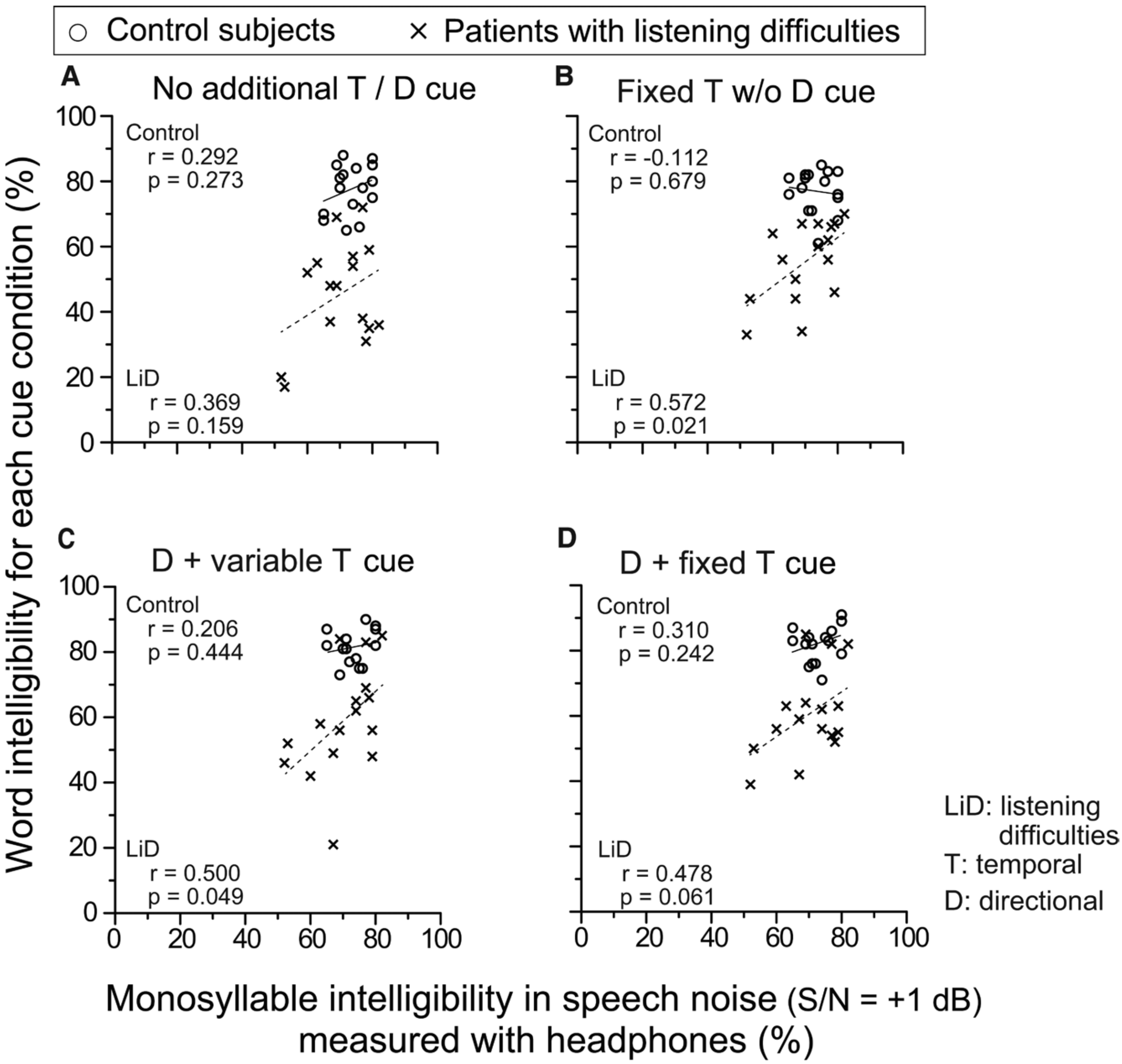

Fig. 6. Relationship between speech intelligibility in the presence of noise in clinical measurements using headphones (signal to noise ratio [S/N] = 1 dB condition) and word intelligibility obtained in the present study for each cue condition for all participants (control subjects [open circles] + patients with listening difficulties [crosses]). Dotted lines in each figure indicate regression lines for the plotted data. *P* values found to be significant after FDR correction are shown in bold. FDR indicates false discovery rate.

Concerning the maximum speech intelligibility for monosyllables in speech noise as assessed using the headphone system, it was not significantly different between the control group and the patient group with listening difficulties (although average intelligibility for the control group tended to be better than that for the patient group with listening difficulties). Word intelligibilities obtained in the present spatial cocktail party situation were apparently worse in the patient group compared with the control group (Fig. 4). There were many methodological differences between the two measurements, so it is difficult to determine exactly which factors caused the difference in intelligibility due to the different measurement methods. However, given that the ability of spatial hearing, which uses auditory cues from both ears to help spatially separate sounds arriving from different directions (Arbogast et al. 2002; Culling et al. 2004; Cameron and Dillon 2008; Stavrinos et al. 2020), has been reported to be poorer in patients with listening difficulties compared with healthy controls (Cameron et al. 2006; Cameron and Dillon 2008), the spatial separation of sound sources in the present cocktail party conditions, but not in the speech in noise assessed under headphones, may be a key factor in explaining the difference. Moreover, the fact that we randomly changed the presentation direction of the target stimuli in the present study may have been one of the factors that caused the different results between the two measurements. That is, in the clinical setting, we sometimes sense some discrepancies between patients' complaints about listening difficulties in the presence of noise and auditory tests mainly using a fixed sound source (regardless of whether a headphone or a loudspeaker system is used). These discrepancies may result in part from the characteristics of the measurements using a fixed sound source, in which it is assumed that selective attention is more enhanced in listening tasks with a fixed sound source than in actual listening environments. In real life, it is often necessary to listen to a speech signal that is presented suddenly from an unexpected direction together with multiple distracting sounds. In any case, the results suggest that the types of measurement conditions and methods used are very important in evaluating the degree of listening difficulties in patients with listening problems.

On the Significant Difference in PTA Between the Control and Patient Groups

As shown in Figures 1A, B, the PTA obtained from patients with listening difficulties was slightly but significantly worse than that obtained from control subjects. In the present study, we did not evaluate inner ear and cochlear nerve function, such as ABR and OAE, in the control group, so we cannot accurately determine whether this difference was due to differences in the condition of the inner ear and cochlear nerve of the subjects. However, considering the fact that the OAE and ABR in the patient group showed no obvious abnormalities and a previous report that cognitive function affects auditory thresholds (Brännström et al. 2020), this difference may also have been due to possible problems in the cognitive system as an attention problem in the patient group.

CONCLUSION

The results of this study show the usefulness of the presentation of directional cues for speech comprehension in the cocktail party situation in patients with listening difficulties, as well as the importance of evaluating the degree of listening difficulties spatially in the cocktail party situation. However, further examinations using different S/N ratios will be necessary to fully elucidate the cueing effects on speech comprehension in the cocktail party environment.

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The authors have no conflicts of interest to disclose.

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