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RESEARCH ARTICLE

Multisensory Speech Processing in Adults with Normal Hearing and Hearing Loss: A Preliminary EEG Study

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Abstract

Studies have shown improvements in speech understanding and quality of life with the use of hearing devices. However, even with that improvement, individuals do not always show the same performance in real-world communication settings. Considering that the communication process involves multisensory integration, this study examined speech recognition performance and brain activity in adults with normal hearing (NH) and hearing loss (HL) in auditory only (AO), visual only (VO), and audiovisual (AV) conditions. Twenty adults with NH and 20 adults with HL completed a speech recognition test while electroencephalography (EEG) was recorded in AO, VO, and AV. Power spectral density values were analyzed for the delta, theta, alpha, beta, and gamma bands. The NH group showed significantly better speech performance than the HL group in AO and AV, while the HL group showed significantly better performance in VO. Regarding EEG characteristics, significant condition effects were observed in the theta and alpha bands in the left hemisphere and in the delta, theta, and alpha bands in the right hemisphere. A significant group-by-condition interaction was observed for the gamma band in the left hemisphere, with the HL group showing greater activity in VO and AV. The findings suggest that multisensory speech processing differs according to both sensory modality and hearing status, and visual input may play an important role in individuals with HL.

Keywords: Hearing loss, Electroencephalography, Multimodal integration

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Introduction

The negative impacts of hearing loss (HL), which is the difficulty of hearing, have been reported in numerous studies. Individuals with HL often experience difficulties in speech perception, which can lead to communication challenges, reduced academic and occupational performance as well as social isolation (Elbeltagy, 2020; Shan et al., 2020; Svinndal et al., 2020). Previous studies have reported improvements in speech perception and quality of life following hearing aid use (Laske et al., 2009; Most et al., 2012; Seol & Moon, 2022; Snapp, 2019). However, hearing aid use does not always lead to positive outcomes (Chiriboga et al., 2022; Glyde et al., 2011; Wong et al., 2018). Even when outcome measures show improved auditory performance, individuals with HL may still complain of difficulties understanding speech in noise, which can ultimately lead to hearing aid return. This discrepancy between test results and real-world communication ability may stem from how outcome measures are performed in clinical settings. In laboratory settings, as opposed to real-world communication involving auditory, visual, and cognitive factors, most tests are performed in sound-treated booths with auditory stimuli only (Jerger, 2011). Consequently, it is difficult to comprehensively evaluate communication ability based solely on peripheral auditory measures, such as speech recognition or hearing thresholds.

Auditory characteristics can be assessed using both subjective and objective methods. Subjective methods include behavioral tests, such as pure-tone audiometry, which measures hearing thresholds from 250 to 8000 Hz using headphones or insert earphones. Objective methods evaluate neurophysiological responses, which include the auditory brainstem response and auditory steady-state response. Because behavioral tests can be influenced by several factors (i.e., age), objective tests are often used for populations that cannot provide reliable behavioral responses (i.e., infants) or when neurological diagnoses (i.e., acoustic neuroma) are needed. Among objective methods, electroencephalography (EEG) is widely used in auditory research along with magnetoencephalography and magnetic resonance imaging (Savers et al., 1974). Compared to other neuroimaging techniques, EEG is cost-effective, noninvasive, and offers excellent temporal resolution, allowing real-time monitoring of brain activity without exposure to magnetic fields (Seol & Shin, 2024). EEG can be analyzed across time and frequency domains. In the time domain, components such as P1 (a positive peak around 50 ms after stimulus onset) and N1 (a negative peak around 100 ms) are often examined. In the frequency domain, EEG activity is classified into delta (<4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (>30 Hz) bands (Min, 2009). Previous studies have reported that speech perception and multisensory processing are primarily associated with theta, alpha, beta, and gamma activity, whereas increased delta and theta activity has been reported in individuals with HL (Basar, 2013; Gnanateja et al., 2022; Senkowski et al., 2006). In addition, activity in the delta and theta bands has been associated with speech clarity and comprehension (Etard & Reichenbach, 2019), alpha band activity has been related to continuous speech listening and attentional engagement (Boudewyn & Carter, 2018; Seifi Ala et al., 2020), and beta and gamma activity have been associated with audiovisual (AV) prediction and multisensory modulation (Karthik et al., 2021; Roa Romero et al., 2015). Thus, frequency domain analysis of EEG may complement time domain analysis of EEG by characterizing neural activity during speech processing across different sensory modalities. However, the specific roles of these frequency bands in multimodal speech recognition remain unclear.

EEG studies on multimodal integration in individuals with NH and HL have mainly compared auditory only (AO) and AV conditions (Davis et al., 2008; McDaniel et al., 2018; Schierholz et al., 2017), or congruent and incongruent AV stimuli (Jenson, 2021; Kaiser et al., 2005), often focusing on individuals with severe to profound sensorineural HL. Recent studies have emphasized that the contribution of visual information to speech in individuals with HL varies according to age, linguistic level, and HL-related factors (Choi et al., 2024). Studies utilizing electrophysiological techniques have also incorporated visual only (VO) speech for those with NH and HL, reporting that visual speech can modulate auditory cortical responses, neural speech tracking and hemispheric response patterns (Frei et al., 2024; Layer et al., 2022). Considering that people with HL tend to rely more on visual cues, such as lip movements and facial expressions, for communication (Erber, 1972; Moradi et al., 2016), these findings highlight the importance of examining how visual stimuli influence speech recognition and sensory modality processing in the central auditory system. However, understanding of visual information processing in the central auditory system and its role in sentence recognition remains limited due to differences in participant populations, experimental paradigms, and data analysis methods. Therefore, the aim of the study was to investigate speech performance and hemisphere-level EEG characteristics in AO, VO, and AV in individuals with NH and HL using frequency band analysis.

Materials and Methods

Participants

The inclusion criteria were as follows: 1) adults aged 19 years or older and 2) native Korean speakers. Individuals with neurological, otological, cognitive, learning, language, or visual disorders other than HL were excluded from the study. Participants were divided into NH and HL groups based on their four-frequency (500, 1000, 2000, and 4000 Hz) pure-tone averages, with 25 dB HL or less classified as the NH group and 26 dB HL or higher classified as the HL group. The HL group consisted of individuals with bilateral sensorineural HL. All experimental procedures were approved by Ewha Womans University's Institutional Review Board (ewha-202307-0003-08). Participants were fully informed about the background, purpose, and procedures of the study and signed an informed consent form prior to participation. All participants were right-handed. Participant characteristics are shown in Table 1.

Table 1. Participant characteristics

	NH (n=20)	HL (n=20)
Age (Years)	47.7(4.20)	47.1(4.12)
Pure-tone average in the right ear (dB HL)	4.4(4.20)	91.7(15.24)
Pure-tone average in the left ear (dB HL)	4.2(4.80)	87.6(21.73)
Duration of HL (Months)	N/A	345.5(22.40)

NH: normal hearing, HL: hearing loss. Values are presented as mean (standard deviation).

Speech Testing

To evaluate sentence recognition performance across AO, VO, and AV, sentences from the Korean Standard Sentence Lists for Adults (KS-SL-A), which has a total of 80 sentences (10 sentences per list), were used. Sentences were recorded in both audio and video by a female talker (Fig. 1). In AO, the recorded sentences were presented through a loudspeaker (YAMAHA, Japan) positioned 1 meter in front of the participant. In VO, silent video recordings were presented on a 27-inch monitor placed 1 meter in front of the participant. In AV, both audio and visual stimuli were presented simultaneously via the loudspeaker and monitor. The presentation level was 60 dBA, which corresponds to a typical conversational level. For each participant, two KS-SL-A lists were assigned to each test condition and no list was repeated across conditions within the same participant. The order of the test conditions was also randomized. All participants completed a practice trial before testing to familiarize themselves with the task. Participants were instructed to repeat each sentence after a beep sound presented at the end of each sentence. Sentence recognition scores were calculated as the percentage of correctly repeated sentences, with each sentence scored as 1 for a correct response and 0 for an incorrect response.

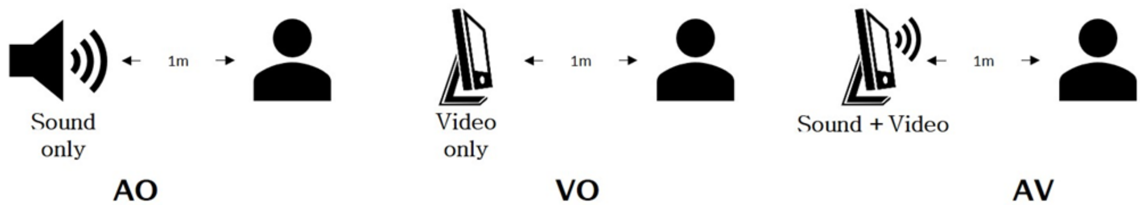

Fig. 1. Experimental setup

EEG Testing

EEG was recorded simultaneously during speech testing using a BrainAmp system (Brain Products GmbH, Germany) with a sampling rate of 1000Hz. EEG was acquired using 32 electrodes placed according to the International 10–20 System, including electrodes over the left and right mastoids. The electrode sites were as follows: Fp1, Fz, F3, F7, FT9, FC5, FC1, C3, T7, TP9, CP5, CP1, Pz, P3, P7, O1, Oz, O2, P4, P8, TP10, CP6, CP2, Cz, C4, T8, FT10, FC6, FC2, F4, F8, and Fp2. The ground electrode was placed on the forehead and the reference electrode was placed on FCz. The experimental paradigm is shown in Fig. 2. After participants completed practice trials to ensure familiarity with the task, the experiment began. In each trial, instructions were displayed for 10 seconds to allow participants to prepare, and the test sentence was presented for four to seven seconds depending on the sentence. A beep (0.5s) was presented at sentence offset, indicating the onset of the repetition period. Each condition was repeated twice.

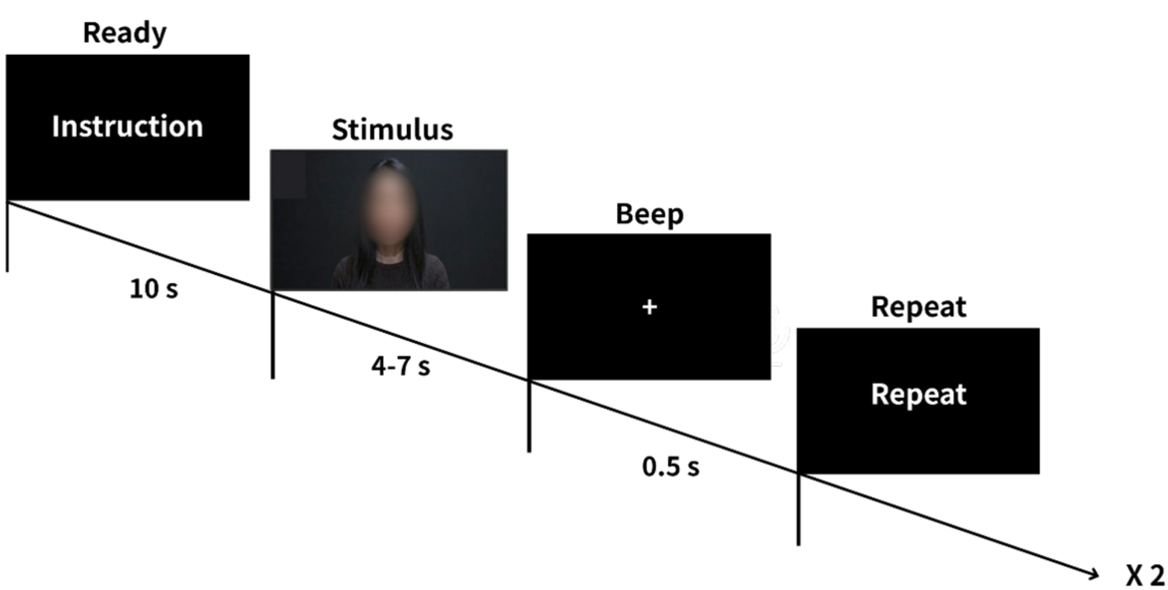

Fig. 2. An example trial of the experimental paradigm

EEG Preprocessing

Following data acquisition, preprocessing was conducted using BrainVision Analyzer (Brain Products GmbH). The EEG data were re-referenced to the averaged mastoid electrodes and band-pass filtered (1-50 Hz). Ocular and movement-related artifacts were corrected using independent component analysis (ICA). Components associated with eye blinks and muscle activity were removed and the EEG signals were reconstructed using inverse ICA. The data were then segmented into epochs and baseline correction was applied. Lastly, artifact rejection was performed. Frequency-domain analyses were performed using MATLAB (R2023b; The MathWorks Inc., USA) with the EEGLAB toolbox (Delorme & Makeig, 2004) and custom scripts.

EEG Data Analysis

In this study, the right and left hemispheres were the main regions of interest. Hemisphere-level analysis was chosen because prior studies have demonstrated hemispheric asymmetries in speech envelope coding, functional lateralization during degraded speech processing, and right hemispheric auditory responses to visual speech (Abrams et al., 2008; Davis et al., 2008; Frei et al., 2024; Liikkanen et al., 2007). In conventional scalp EEG, spatial resolution is limited due to volume conduction as each electrode represents overlapping neural sources rather than one single area (Michel & Murray, 2012; Srinivasan et al., 2007). The electrodes included for the left hemisphere were Fp1, F3, F7, FC5, FC1, C3, T7, CP5, CP1, P3, P7, TP9, and O1. The electrodes included for the right hemisphere were Fp2, F4, F8, FC2, FC6, C4, T8, CP2, CP6, TP10, P4, P8, and O2. Midline electrodes (Fz, Cz, Pz, and Oz) were not included as the primary analysis focused on hemisphere-level comparisons. EEG analysis was conducted on the 0-4 second time window following sentence onset. For both hemispheres, the power spectral density (PSD) was calculated for five frequency bands: delta (1–3 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (14–30 Hz), and gamma (31–50 Hz) within the 0–4 second time window following sentence onset. This corresponded to the shortest sentence duration across stimuli and was used as a common analysis window across all trials. At the sampling rate used in this study, the four-second analysis window corresponded to 4000 samples per channel. PSD represents the distribution of EEG signal energy across frequencies; higher PSD values in a given band indicate increased oscillatory activity in that frequency range.

Statistical Analysis

Statistical analyses were performed using SigmaPlot version 14.0 (Systat Software Inc., USA). For speech performance, a two-way mixed analysis of variance (ANOVA) was conducted with group (NH and HL) as the between-subject factor and condition (AO, VO, and AV) as the within-subject factor. For EEG, a two-way mixed ANOVA was performed for each hemisphere (left and right) and each frequency band (delta, theta, alpha, beta, and gamma) using hemisphere-level PSD as the dependent variable. In all analyses, group and condition were treated as the between-subject and within-subject factors, respectively. When a significant main effect of condition or a significant group-by-condition interaction was observed, post hoc comparisons were performed using the Bonferroni correction.

Results

Speech Performance

The mean sentence recognition scores in AO, VO, and AV are shown in Table 2. Except for the VO condition, the NH group demonstrated higher sentence performance than the HL group in AO and AV. Statistical analysis revealed significant main effects of group ($F(1,38)=124.147$, $p<0.001$) and condition ($F(2,76)=119.700$, $p<0.001$). A significant interaction effect between group and condition was also observed ($F(2,76)=129.525$, $p<0.001$). Post-hoc analyses indicated significant differences between AO and VO conditions ($t=19.119$, $p<0.001$) and between AV and VO conditions ($t=19.119$, $p<0.001$) in the NH group. Within-group comparisons revealed significant differences between AV and AO ($t=3.296$, $p=0.004$) in the HL group. Between-group comparisons showed that those with NH performed significantly better in AO ($t=14.956$, $p<0.001$) and AV ($t=12.202$, $p<0.001$) than the HL group. The HL group performed significantly better in VO ($t=2.716$, $p=0.008$) than the NH group.

Table 2. Average speech performance (%) in both groups

Conditions Groups	AO	VO	AV
NH	98.0(3.4)	3.5(5.40)	97.8(4.1)
HL	9.5(29.3)	19.5(17.4)	25.7(29.5)

AO: auditory only, VO: visual only, AV: audiovisual, NH: normal hearing, HL: hearing loss. Values are presented as mean (standard deviation).

EEG Characteristics

Fig. 3 illustrates the scalp topographies for both groups under each condition across frequency bands. The normalized PSD values for each hemisphere across test conditions are presented in Table 3. In the left hemisphere, significant main effects of condition were observed in the theta and alpha bands, whereas a significant group-by-condition interaction was observed in the gamma band. For the theta band, condition had a significant effect ($F(2,76)=14.424$, $p<0.001$) and post-hoc analysis showed that theta band activity was higher in AO than in VO ($t=5.368$, $p<0.001$), AO than in AV ($t=2.536$, $p=0.040$), and AV than in VO ($t=2.833$, $p=0.018$). For the alpha band, a significant main effect of condition was also found ($F(2,76)=6.871$, $p=0.002$) with significantly greater alpha band activity in AO than in AV ($t=3.416$, $p=0.003$) and VO ($t=2.955$, $p=0.012$). In the gamma band, a significant group-by-condition interaction was observed ($F(2,76)=4.684$, $p=0.012$). Post-hoc analysis revealed that the HL group exhibited significantly higher gamma band activity than the NH group in VO ($t=2.121$, $p=0.036$) and AV ($t=2.259$, $p=0.026$). In the right hemisphere, significant main effects of condition were observed in the delta, theta, and alpha bands. The delta band had a significant effect of condition ($F(2,76)=6.404$, $p=0.003$) and post-hoc analysis revealed significantly greater delta band activity in AO than in VO ($t=3.506$, $p=0.002$). In the theta band, a significant main effect of condition was also observed ($F(2,76)=12.250$, $p<0.001$), with post-hoc analysis indicating greater activity in AO than in VO ($t=4.604$, $p<0.001$) and AV ($t=3.877$, $p<0.001$). Lastly, the alpha band showed a significant main effect of condition ($F(2,76)=10.093$, $p<0.001$) with higher alpha band activity in AO than in AV ($t=3.915$, $p<0.001$) and VO ($t=3.867$, $p<0.001$).

Table 3. Normalized PSD of hemisphere across test conditions

Characteristics		NH			HL		
		AO	VO	AV	AO	VO	AV
Delta	LH	0.54(0.16)	0.49(0.21)	0.56(0.14)	0.56(0.15)	0.43(0.16)	0.48(0.21)
	RH	0.55(0.13)	0.44(0.18)	0.49(0.14)	0.55(0.11)	0.42(0.15)	0.45(0.20)
Theta	LH	0.64(0.11)	0.47(0.15)	0.59(0.16)	0.63(0.17)	0.46(0.15)	0.51(0.17)
	RH	0.57(0.09)	0.43(0.18)	0.49(0.14)	0.59(0.13)	0.47(0.10)	0.44(0.14)
Alpha	LH	0.64(0.15)	0.46(0.19)	0.46(0.18)	0.56(0.20)	0.52(0.16)	0.47(0.13)
	RH	0.58(0.13)	0.40(0.15)	0.46(0.14)	0.54(0.14)	0.46(0.17)	0.40(0.13)
Beta	LH	0.50(0.19)	0.41(0.14)	0.43(0.14)	0.46(0.17)	0.48(0.15)	0.44(0.13)
	RH	0.44(0.15)	0.39(0.15)	0.38(0.10)	0.43(0.13)	0.44(0.10)	0.41(0.12)
Gamma	LH	0.42(0.18)	0.36(0.15)	0.31(0.13)	0.35(0.15)	0.47(0.17)	0.42(0.14)
	RH	0.38(0.13)	0.38(0.13)	0.29(0.09)	0.36(0.13)	0.43(0.12)	0.39(0.12)

PSD: power spectral density, LH: left hemisphere, RH: right hemisphere, AO: auditory only, VO: visual only, AV: audiovisual, NH: normal hearing, HL: hearing loss. Values are presented as mean (standard deviation).

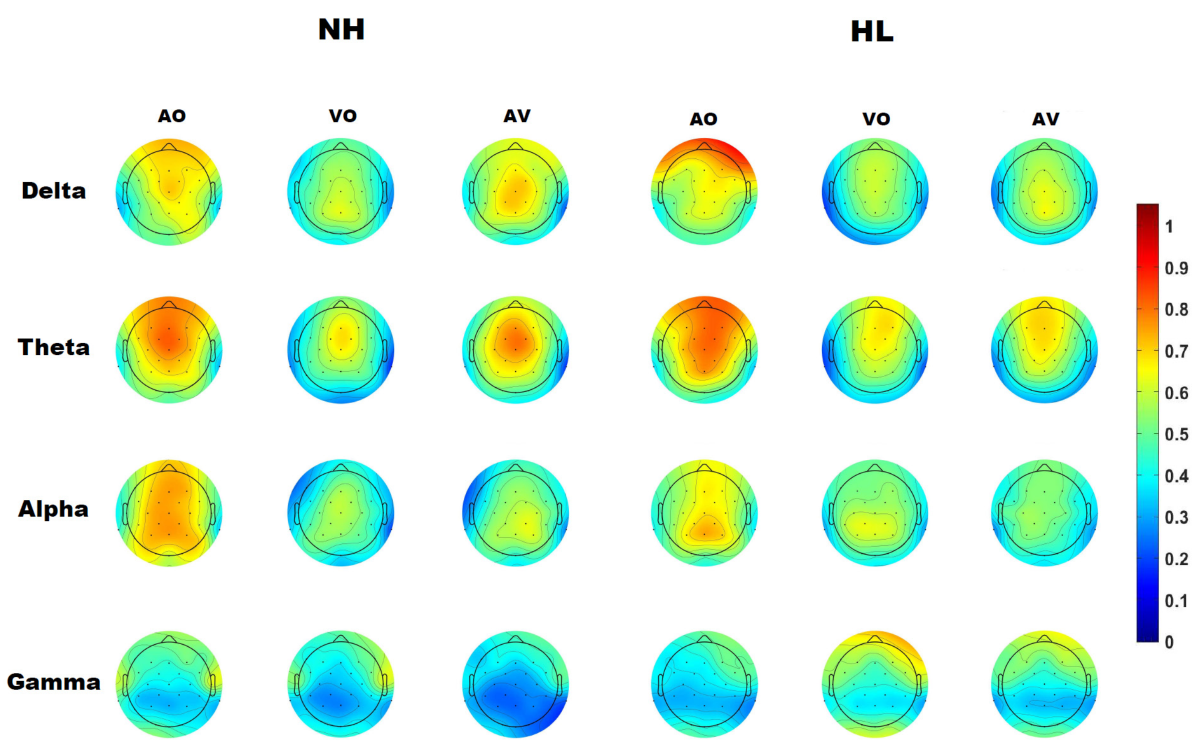

Fig. 3. Scalp topographies of mean PSD for NH and HL groups across AO, VO, and AV. Only frequency bands showing significant effects in the hemisphere-level analysis are displayed.
Note. PSD: power spectral density, AO: auditory only, VO: visual only, AV: audiovisual, NH: normal hearing, HL: hearing loss.

Discussion

This study examined not only the individual contributions of auditory and visual information (AO and VO) but also AV integration in adults with diverse auditory characteristics, while simultaneously evaluating brain activity objectively across frequency bands. When comparing sentence recognition performance, the NH group showed significantly higher speech understanding than the HL group in AO and AV conditions while the HL group showed significantly higher speech recognition performance than the NH group in VO. Within-group comparisons revealed that the NH group showed similarly high performance in AO and AV, but the HL group showed higher performance in AV than in AO. These findings suggest that auditory input remained critical for the NH group and those with HL may have relied more strongly on visual input and experienced AV benefit. This is consistent with previous studies illustrating that individuals with HL rely on visual cues, such as lip movements and facial expressions, for speech perception (Bahrick et al., 2018; Erber, 1972; Hillairet de Boisferon et al., 2018; Lewkowicz & Hansen-Tift, 2012; Moradi et al., 2016).

When EEG characteristics across AO, VO, and AV conditions were analyzed by hemisphere, statistically significant effects of condition were observed in both hemispheres, but the patterns differed across frequency bands. In the left hemisphere, significant condition effects were observed in the theta and alpha bands, and a significant group-by-condition interaction was observed in the gamma band. In the right hemisphere, significant condition effects were observed in the delta, theta, and alpha bands. AO generally elicited greater neural activity compared to VO and AV, suggesting that patterns of neural activity were most apparent in conditions containing auditory input. These findings partially align with previous findings showing that low-frequency activity is involved in speech tracking and temporal parsing, and that visual speech can modulate neural processing during AV speech perception (Etard & Reichenbach, 2019; Frei et al., 2024; Layer et al., 2022; Schroeder et al., 2008). The condition effects observed in the right hemisphere could indicate relatively stronger right hemisphere involvement in modality-dependent speech processing, which is in line with prior studies linking the right hemisphere to speech envelope coding, degraded speech processing, and AV speech perception (Abrams et al., 2008; Alpert et al., 2008; Davis et al., 2008; Liikkanen et al., 2007).

Alpert et al. (2008) demonstrated that AV stimuli elicited the earliest activation in the right Heschl's gyrus, implying that right hemisphere activity may increase when auditory signals are ambiguous or accompanied by visual cues. In addition, the significant interaction observed for the gamma band in the left hemisphere indicates that group-related differences were selectively observed under conditions involving visual input, as the HL group showed greater gamma activity than the NH group in VO and AV. Since the gamma band has been linked to multisensory and higher-order sensory processing, this finding could indicate that individuals with HL recruited greater neural resources when visual speech information was available (Basar, 2013; Senkowski et al., 2006). Overall, the findings of the study suggest that even when behavioral assessments (i.e., hearing threshold or speech intelligibility tests) indicate good performance, differences in central auditory processing can be detected at the neural level depending on individuals' auditory characteristics (Seol et al., 2025). Therefore, comprehensive communication assessments should not be limited to peripheral auditory function but should also include evaluations of multisensory integration within the central auditory system.

Although this preliminary study included 20 participants in each group, subsequent studies with larger samples are needed to enhance the generalizability, reliability, and validity of multisensory integration paradigms. Future studies should consider subgroup analyses based on degree and type of HL, type of hearing device, and duration of device use to better characterize EEG patterns associated with different auditory profiles. Since the present study used hemisphere-level ROI averages as the primary analysis, more spatially specific neural differences may not have been fully captured. In addition, because the brain comprises various functionally distinct regions, including the temporal, occipital, and frontal lobes, future studies would benefit from incorporating channel-wise analyses, functional connectivity, and source localization analysis to examine the specific brain regions and neural networks most strongly involved in multisensory speech processing. Such approaches may provide a more detailed understanding of how auditory and visual information are integrated in individuals with HL, ultimately contributing to the development of personalized assessment and rehabilitation tools for individuals with HL.

Conclusion and Implications

This study examined speech performance and electrophysiological characteristics across AO, VO, and AV conditions in adults with NH and HL using EEG. In terms of behavioral performance, the NH group showed better speech performance than the HL group in AO and AV. The HL group, on the other hand, showed better speech performance in VO, suggesting greater reliance on visual input in this population. In terms of EEG, patterns of neural activity differed by modality in the theta and alpha bands in the left hemisphere and in the delta, theta, and alpha bands in the right hemisphere. These findings indicate that multisensory speech processing involves different neural dynamics depending on sensory modality and auditory characteristics. Therefore, evaluating communication ability in individuals with HL should extend beyond behavioral measures to include assessments of central neural processing incorporating visual speech. These findings may also be beneficial for establishing rehabilitation approaches that incorporate visual cues and AV training to support more effective communication for this population.

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Conflicts of Interest

The authors declared no conflicts of interest

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