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RESEARCH ARTICLE

Speech Perception in Individuals with Normal Hearing and Hearing Loss: A Multimodal fNIRS study

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Abstract

Hearing loss (HL) affects the quality of life, with significant impacts on health, communication, social, and emotional interactions, leading to isolation and difficulties in social activities. Communication, the most common challenge reported by individuals with HL, involves the integration of various sensory inputs. Accurate assessment of communication ability involves not only evaluating how well speech is heard but also understanding how different sensory inputs are processed in the brain. Using the functional near-infrared spectroscopy (fNIRS) technique as an objective method, this pilot study explored speech performance and the activation patterns of the anterior prefrontal cortex (APFC) in individuals with normal hearing (NH) and HL.

Twenty-six participants (14 with NH and 12 with HL) completed speech and fNIRS testing in auditory only (AO), visual only (VO), and audiovisual (AV) conditions with five trials per condition. The participants completed a listen-and-repeat task and speech performance was evaluated using percent-correct scores. Hemodynamic responses in APFC were analyzed to investigate the activation patterns in each test condition.

Both groups showed the best speech performance in AV, followed by AO and VO. While the NH group showed better speech performance than the HL group in AV and AO, the HL group showed better performance in VO. In terms of APFC activation patterns, both groups exhibited activation in the right anterior medial PFC across AO, VO, and AV, but in VO, the HL group showed activation in that left anterior lateral PFC.

These pilot study results are consistent with previous findings showing that individuals with HL exhibit lower speech performance and the provision of visual information is beneficial for speech understanding regardless of HL. However, different patterns of APFC activation observed through fNIRS indicate that the areas engaged in processing various sensory inputs during communication may differ depending on the presence of HL.

Keywords: Hearing loss, speech perception, communication, fNIRS, audiovisual integration

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Introduction

Hearing loss (HL), as a global health issue, adversely affects quality of life. In 2019, HL prevalence was already estimated to be 1.57 billion (Haile et al., 2021) and the negative impact of HL on multiple dimensions of life has been documented in numerous studies (Ciorba et al., 2012; Punch et al., 2019; Roland et al., 2016; Ronner et al., 2020; Saadati Borujeni et al., 2015; Umansky et al., 2011). HL was shown to negatively impact health, communication, social, and emotional interactions, leading to communication disorders, difficulties with family interactions, feelings of loneliness, and reluctance to engage in social activities (Ciorba et al., 2012; Lotfi et al., 2009; Punch et al., 2019). At the societal level, untreated HL can lead to significant social and economic costs (Huddle et al., 2017; McDaid et al., 2021; Organization, 2017). In 2017, the World Health Organization has reported a financial burden exceeding US $750 billion, including educational support, loss of productivity, and societal expenses, annually on the global economy (World Health Organization, 2017). In 2021, McDavid and colleagues reported that the global costs of HL exceeded $981 billion and this cost was related to decline in quality of life and healthcare costs associated with individuals with HL (McDaid et al., 2021).

Communication, one of the most common difficulties faced by people with HL, relies on the real-time integration of both auditory and visual information. The concept of audiovisual (AV) integration was first introduced in 1976 through the McGurk effect (McGurk & MacDonald, 1976). In the study by McGurk and MacDonald, when one syllable was dubbed over another, participants accurately repeated the syllable when only the auditory stimulus was presented. However, when viewing the dubbed film, they repeated a different syllable, demonstrating that visual input plays a significant role in speech perception, which was previously thought to involve only auditory process. Since then, numerous studies have been conducted on multisensory integration in human communication (Kirk et al., 2002; Puschmann et al., 2019; Seol et al., 2021; Sumby & Pollack, 1954). Sumby and Pollack (1954) investigated the benefit of visual information on speech understanding even in the presence of noise. In this study, speech performance in quiet and noise conditions was compared under auditory only (AO) and AV conditions. For the noise condition, speech performance was evaluated across various signal-to-noise ratios. As expected, speech performance was better in quiet than in noise, and better under AV than AO. This demonstrated that the addition of visual information aids speech understanding, with this benefit being particularly pronounced at lower signal-to-noise ratios where the noise is louder than the signal, making listening more challenging. The benefit of visual information was also observed in studies involving individuals with HL (Kirk et al., 2002; Puschmann et al., 2019; Tye-Murray et al., 2007). In a study by Kirk et al. (2002), children with prelingual HL and adults with postlingual HL showed highest performance in AV than in AO and visual only (VO) condition. Not only visual information but also the use of hearing devices has been shown to aid speech understanding, especially for individuals with HL (Ellsperman et al., 2021; Hainarosie et al., 2014; Ketterer et al., 2020; Seol & Moon, 2022). However, despite these research findings, some individuals do not show improvement in speech understanding after wearing a hearing device (Stropahl et al., 2017). Speech performance is typically used as an indicator when assessing the benefit of hearing devices, and factors such as duration of device use and severity of HL are known to influence speech performance (Bernhard et al., 2021; Gallagher & Woodside, 2018). However, the underlying mechanism remain unclear, and objective methods, such as neuroimaging and electrophysiological techniques, provide valuable insights into how HL and hearing device use affect brain processing, helping to uncover factors that might not be captured by behavioral assessments alone (Sandmann et al., 2015; Seol et al., 2024; Stropahl et al., 2017).

Objective methods commonly used in auditory research include functional magnetic resonance imaging (fMRI), electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET), and functional near-infrared spectroscopy (fNIRS) (Providência & Margolis, 2022; Seol & Shin, 2024). These neuroimaging modalities have their own distinct pros and cons. First, fMRI may offer not only cortical but also deep brain images in high spatial resolution; however, it has poor temporal resolution and requires a confined environment such as a shielded room (Logothetis, 2008). EEG provides excellent temporal resolution in the order of milliseconds and is cost-effective, but its spatial resolution is limited and highly susceptible to motion artifacts and electromagnetic noises (Luck, 2014). MEG combines high temporal resolution with better spatial localization than EEG but is highly expensive and requires specialized facilities (Hämäläinen et al., 1993). PET is practical for examining metabolic processes but involves radioactive exposure, which makes it unsuitable for repeated measurements (Raichle, 1998). fNIRS is a technique that evaluates brain activation by measuring concentration changes in oxygenated and reduced hemoglobin using near-infrared light. Although its spatial resolution and penetration depth are limited (Ferrari & Quaresima, 2012), fNIRS offers the advantages of being more affordable, portable, and less susceptible to artifacts caused by movement, making it particularly suitable for use with children as well as individuals wearing hearing devices (i.e., hearing aids or cochlear implants) (Providência & Margolis, 2022; Seol & Shin, 2024). With careful consideration required for its use in individual-level assessments, the shorter testing time with fNIRS also suggests its potential for clinical application. When it comes to auditory research, the use of fNIRS in auditory research has not been as prevalent compared to other techniques. Most studies have been conducted on individuals wearing hearing devices and those with NH, with the investigated regions primarily centered on the temporal lobe (Alemi et al., 2023; Bálint et al., 2022; Butera et al., 2022; Chen et al., 2017; Stropahl & Debener, 2017). Although the temporal cortex is responsible for auditory processing, communication involves the processing of not only auditory information but also various sensory inputs, which are handled by different brain regions. In particular, the prefrontal cortex (PFC) integrates sensory information necessary for language processing, such as attention and working memory (Friederici & Gierhan, 2013; Miller & Cohen, 2001). Therefore, the processing of sensory information in the PFC may differ depending on the presence of HL, but there has been limited research investigating this aspect in both NH and HL groups using fNIRS. The aim of our pilot study was to evaluate speech performance under AO, VO, and AV conditions and to investigate the characteristics of brain activation in the PFC in each condition using fNIRS.

Materials and Methods

Participants

The inclusion criteria were adults aged 19 and above and native Korean speakers. For the NH group, participants with a four-frequency (250, 500, 1000, and 4000 Hz) puretone average of 25 dB HL or less were included, while those with 26 dB HL or higher were classified into the HL group. Individuals who were unable to communicate and understand TV at a distance of 1m and those with neurological and mental disorders were excluded from the study. All experimental procedures were approved by Ewha Womans University's Institutional Review Board and an informed consent document was obtained from the participants. Participant characteristics are shown in Table 1. All participants were right-handed. In the HL group, all participants had bilateral sensorineural HL.

Table 1. Participant characteristics

	NH (n=14)	HL (n=12)
Age (Years)	33.7 ± 13.8	49.3 ± 18.8
Gender (Male:Female)	5:9	6:6
Puretone average in the right ear (dB HL)	3.8 ± 6.2	82.9 ± 15.0
Puretone average in the left ear (dB HL)	3.2 ± 5.9	84.1 ± 15.3
Duration of HL (Months)	N/A	210 ± 127.4

Values are presented as mean ± SD

fNIRS Data Acquisition

The fNIRS data acquisition was conducted in AO, VO, and AV conditions using a NIRSIT LITE device (OBELAB, Seoul, Korea) at a sampling rate of 8.138 Hz. The fNIRS system comprises 15 channels with a 30 mm inter-optode distance, specifically designed for capturing brain activations within the PFC. Test sentences from the Seoul National University Hospital Everyday Sentence Test (SNUH Everyday Sentence Test) were used as the stimuli. The SNUH Everyday Sentence Test consists of a total of seven lists, each containing 10 sentences, and includes a total of 50 keywords. In AO, the sentences were presented from a loudspeaker located 1 m away from the participant at 60 dBA. In VO, the video recording of the male speaker was displayed on a laptop without sound. In AV, the video recording was played on the laptop with sound playing from the loudspeaker at 60 dBA. For each test condition, the experimental paradigm consisted of the stimulus (sentence) presentation period, repetition period and post-task break. Each trial was composed of a 4-second sentence presentation followed by a 4-second sentence repetition, repeated twice. After each trial, a 30-second resting period was provided (Fig. 1). A total of five trials were conducted per test condition, completing 15 trials overall. The total testing time was an hour. Percent-correct scores were calculated based on the number of correctly repeated sentences. Prior to the main experiment, all participants completed practice test to familiarize themselves with the task. The fNIRS device was firmly positioned on the participants' forehead over the anterior PFC (APFC) and carefully adjusted to ensure good signal quality. Moreover, an automatic gain calibration step, implemented by the vendor, was performed to ensure high-quality data acquisition. This calibration was routinely repeated between testing sessions to maintain consistency and reliability in data quality. In this study, the prefrontal regions were prioritized over other areas. While whole-brain measurements could offer deeper insights into task-related brain activations, their clinical applicability is limited and several studies have reported the PFC as the relevant region for cognitive tasks (Koechlin et al., 2003; Naseer & Hong, 2015). In particular, the APFC has been shown to play a crucial role in integrating audiovisual information and processing speech-related tasks, especially when auditory input is degraded or requires additional cognitive resources for interpretation (Duncan & Owen, 2000). Moreover, a previous study has demonstrated that the APFC is involved in compensatory mechanisms when sensory processing regions are insufficient to take care of auditory stimuli (Braga et al., 2013). After the data acquisition, preliminary data processing was conducted using the manufacturer-specific signal processing software.

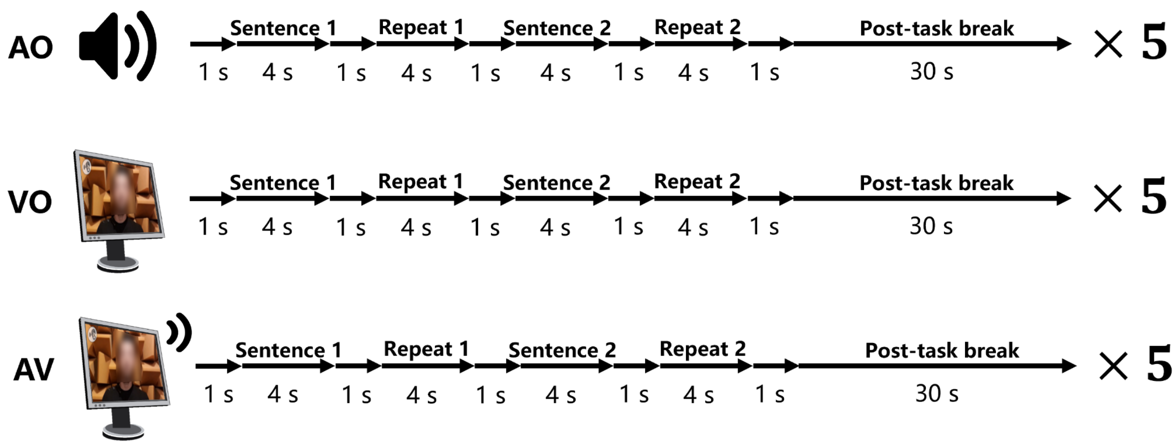

Fig. 1. Experimental paradigm

Preprocessing of fNIRS data

Preprocessing of the fNIRS data involved the following steps. First, raw intensity data measured from the fNIRS device were used to calculate optical density. Then, the optical density signals were converted to oxygenated/reduced hemoglobin ($\Delta HbO/\Delta HbR$). Subsequently, normalization along the sample space was applied to standardize the data such that the standard deviation of data points throughout all channels was equal to one. A zero-phase filtering based on the third-order Butterworth filter with a passband of 0.005–0.04 Hz was employed to remove physiological noises and low-frequency drift, ultimately extracting task-related hemodynamic responses. Epochs were extracted by segmenting the data from -1 to 52 seconds (including task and post-task break) relative to the markers. Baseline correction was conducted by subtracting the average value within the reference interval of -1 to 0 seconds relative to the markers from the epochs on each channel (Kim et al., 2023; Shin, 2020; Shin, 2023). Analysis based on regions of interest (ROI) was also performed in order to investigate the brain activation areas. As shown in Fig. 2, ROIs were defined as follows: Right Anterior Lateral (RAL) PFC included Channels 02, 03, and 04, Right Anterior Medial (RAM) PFC comprised Channels 05, 06, and 07, Left Anterior Medial (LAM) PFC encompassed Channels 09, 10, and 11, and Left Anterior Lateral (LAL) PFC incorporated Channels 12, 13, and 14 (OBELAB, 2022). The fNIRS epochs from all associated channels were averaged for each ROI. The fNIRS epochs for each ROI were aggregated through block averaging to derive the individual block-averaged fNIRS data. All preprocessing procedures were conducted with MATLAB 2024a (MathWorks, Natick, USA).

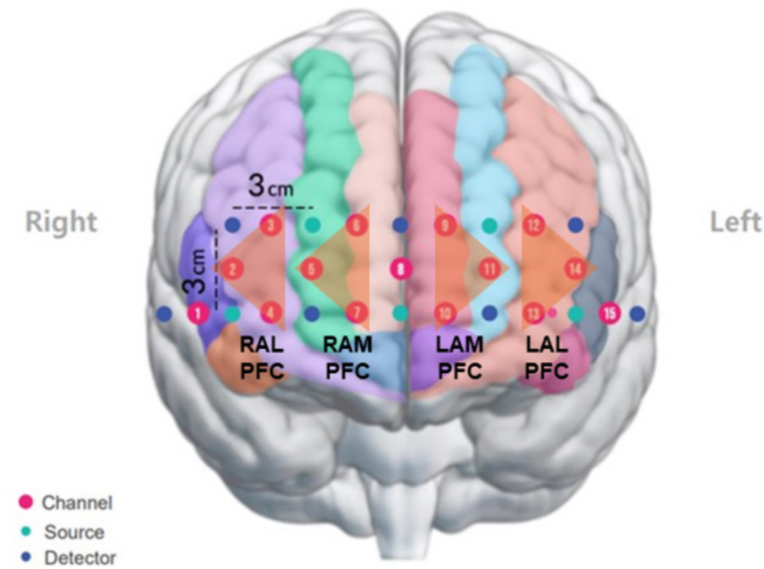

Fig. 2. Locations of fNIRS sources (green circles), detectors (blue circles), and channels (numbered red circles). ROIs are indicated by orange triangular shaded areas.

Quantification of Brain Activation

Brain activation levels for all test conditions (AO, VO, and AV) were quantified by performing linear regression on the block-averaged epoch data for each ROI. Regression coefficients, β, were derived using a theoretical hemodynamic function model (Penny et al., 2011). These coefficients served as quantitative metrics for brain activation in each ROI under the respective task conditions. Due to the relatively small ΔHbR amplitude, which is limited in accurately reflecting brain activation levels, the analysis focused exclusively on ΔHbO-derived data hereafter.

Statistical Analysis

Within the NH and HL groups, brain activation levels under the AO, VO, and AV conditions were evaluated using the computed β. The significance of brain activation differences across the test conditions for each ROI was assessed using Friedman tests to calculate *p*-values. If significant differences were observed, pairwise comparisons were conducted using the Wilcoxon signed-rank test, with *p*-values adjusted through Bonferroni correction. For each test condition, differences in brain activation between the NH and HL groups were examined for each ROI. Due to the unequal sample sizes between the NH and HL groups, permutation tests were employed to evaluate the statistical significance of differences in the average of β. The significance of these differences was reported in terms of *p*-values.

Results

Speech Performance

In terms of speech performance, the NH group showed a mean speech performance of 95.0% in the AO condition, 0.7% in the VO condition, and 95.7% in the AV condition. For the HL group, speech performance was 39.2% in AO, 5.3% in VO, and 51.7% in AV. The NH group showed better speech performance than those with HL in AO and AV conditions. When comparing across modalities, both the NH and HL groups showed the best speech performance in the AV condition, where both visual and auditory stimuli were presented together.

Hemodynamic Responses

Fig. 3(a) and (b) present the grand average of temporal hemodynamic responses across channels for three different task conditions for the NH and HL groups, respectively. For Fig. 3(a), Ch03 displayed distinct ΔHbO across all conditions, with the most prominent activation observed in the AO condition. Similarly, Ch05 and Ch12 exhibit heightened ΔHbO under the AO condition, while Ch10 demonstrates a pronounced negative ΔHbO in the AV condition. In Fig. 3(b), Ch02 exhibits marked brain activation in the AV condition, whereas Ch03 showed distinct ΔHbO exclusively in the AO condition. Ch05, Ch08, and Ch11 revealed significantly negative ΔHbO in the AV condition, while Ch04, Ch13, and Ch14 display prominent ΔHbO in the VO condition.

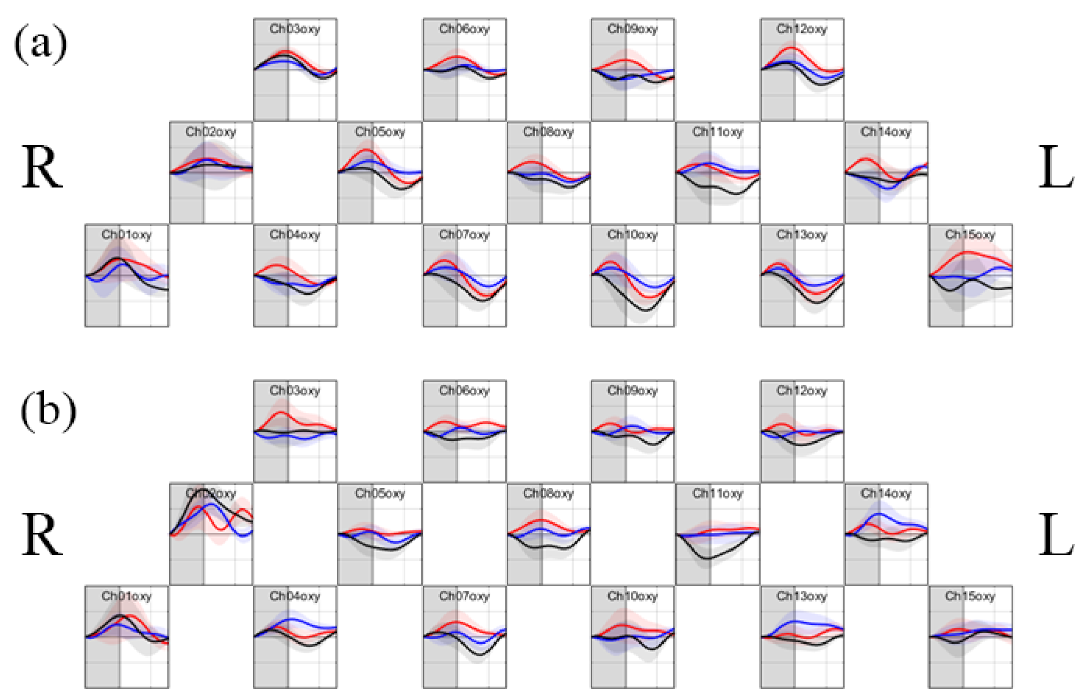

Fig. 3. Grand average of task-related temporal ΔHbO across channels for three task conditions for (a) NH and (b) HL groups. Red, blue, and black correspond to AO, VO, and AV, respectively. The gray shaded interval indicates a task period of 21 seconds. Shaded areas near the solid lines are the standard error of mean. The signal amplitudes were normalized. Note that Ch02 is located in the right hemisphere.

Within-Subject Analysis

Fig. 4 illustrates the mean brain activation levels across task conditions within each ROI, represented by β values. In the NH group, the AO condition consistently evoked the highest brain activation (i.e., the largest β) across all ROIs. Conversely, the VO condition produced minimal brain activation across all ROIs, while the AV condition was associated with negative brain activation (i.e., negative β) in the LAM PFC. However, no significant differences in average β values across task conditions were observed in any ROI (Friedman test, $p > 0.05$). The RAL PFC exhibited heightened brain activation in the HL group across all task conditions. In contrast, negative brain activation was observed in other ROIs during the AV condition. Notably, the LAL PFC demonstrated elevated activation during the VO condition. Nonetheless, no significant differences in average β values across task conditions were identified in any ROI (Friedman test, $p > 0.05$).

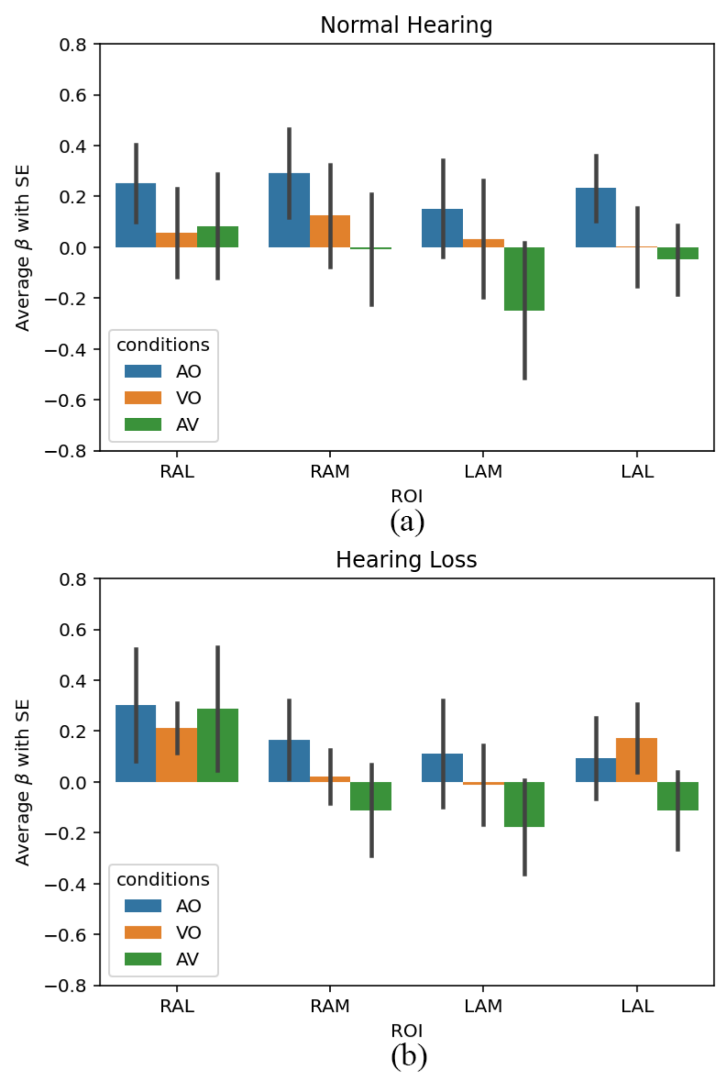

Fig. 4. Within-subject comparison of average β values according to three different task conditions (AO, VO, and AV) in four different ROIs (RAL PFC, RAM PFC, LAM PFC, and LAL PFC): (a) NH group and (b) HL group. The error-bars indicate the standard error of mean.

Between-Subject Analysis

Fig. 5 illustrates the comparison of average β values across ROIs between the NH and HL groups for each task condition. The analysis demonstrated that the RAL PFC region exhibited higher brain activation (i.e., higher β) in the HL group than the NH group across all task conditions, marking it as the region with the most consistent group differences. Conversely, in ROIs apart from the RAL PFC, brain activation under the AO condition was slightly higher in the NH group than in the HL group. The AV condition elicited consistent negative brain activation in the HL group in the same ROIs mentioned above. In contrast, the NH group's brain activation under the VO condition was relatively lower. Nonetheless, no statistically significant differences in average β values between groups were identified for any ROI or task condition, as indicated by the permutation test results ($p < 0.05$).

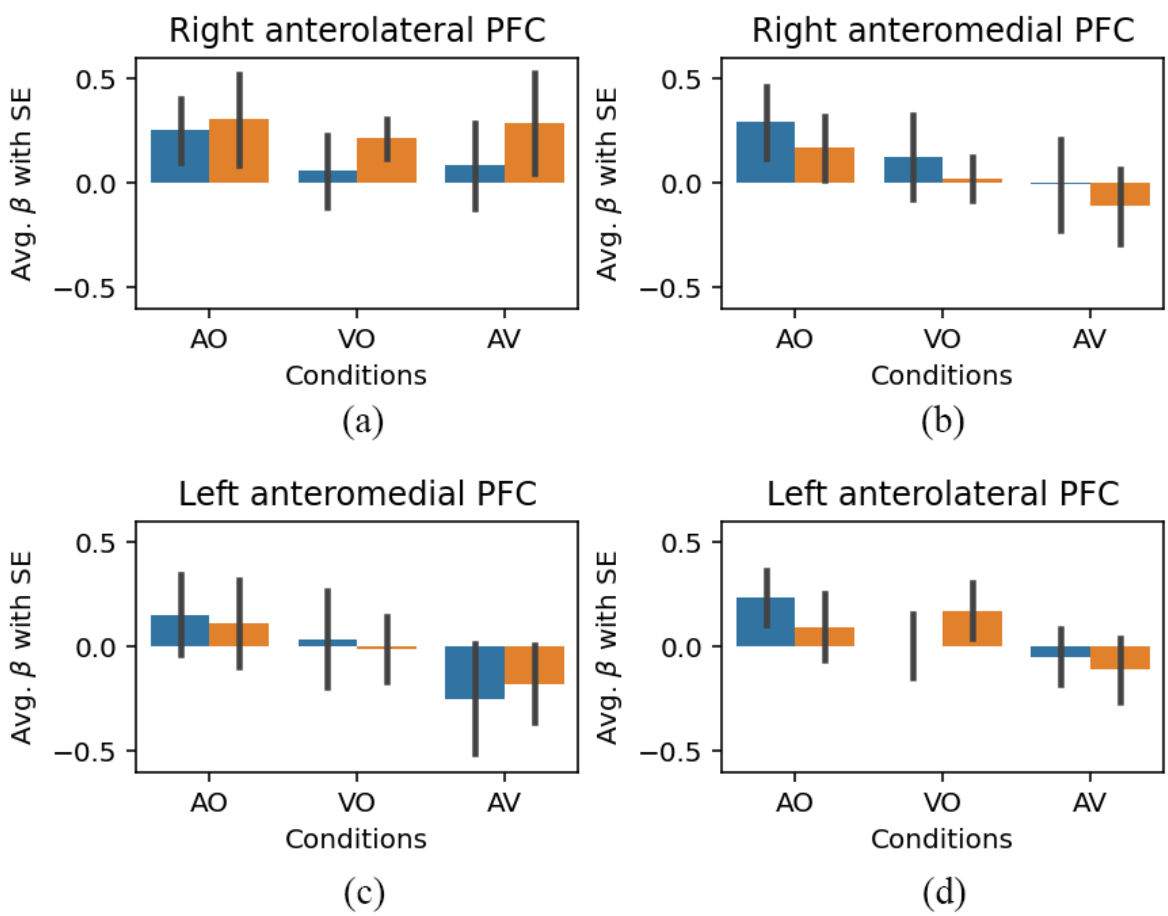

Fig. 5. Between-subject comparison of average β values according to three different task conditions (AO, VO, and AV) in four different ROIs: (a) RAL PFC, (b) RAM PFC, (c) LAM PFC, and (d) LAL PFC. Blue and orange bars are for the NH and HL group, respectively. The error-bars indicate the standard error of mean.

Discussion

The fNIRS technology is well-suited for measuring reliable hemodynamic responses in the PFC, allowing speech perception studies in a naturalistic setting while remaining compatible with hearing devices. Its ability to function without electromagnetic interference makes it particularly suitable for studying individuals with HL, including those using cochlear implants or hearing aids. Leveraging these advantages, our pilot study not only assessed speech understanding by evaluating participants' accuracy in repeating sentences during the listen-and-repeat task but also objectively measured APFC activation patterns using fNIRS. When comparing based on the presence of HL, the NH group understood speech better in the AO and AV conditions, whereas the HL group outperformed in the VO condition. Across all conditions, both groups demonstrated the best speech performance in the AV condition, followed by AO and VO. These findings are in line with previous research that HL negatively affects speech perception and the process of speech understanding involves multisensory integration (Cardin, 2016; Dubno et al., 1984; Woodhouse et al., 2009). In the review on visual speech perception in individuals with NH and HL, Woodhouse et al. (2009) reported the critical role of speech-read cues in speech understanding, noting that even infants utilize these cues. There are also several studies (Desjardins et al., 1997; Knowland et al., 2016; Smith & Bennetto, 2007) reporting difficulties in visual information processing in individuals with not only HL but also disorders such as speech disorders, highlighting the importance of visual information in communication. Regarding hemodynamic responses, findings from our study showed that different areas of the APFC were activated for AO, VO, and AV depending on HL. In the AO and AV conditions, both groups exhibited similar activation patterns, but differences were observed in the VO condition. In the AO condition, all four ROIs (RAL, RAM, LAM, LAL) were activated, and in the AV condition, RAL was activated. However, in the VO condition, the NH group showed the highest activation RAM, RAL, and LAM, while the HL group showed activation in RAL and LAL. Among the PFC regions involved in facial movements, working memory, and the simultaneous presentation of sensory inputs (Koechlin et al., 1999; MacLeod et al., 1998; Romanski, 2012; Romanski & Hwang, 2012), RAL could be highly associated with sensory processing, with a greater degree of involvement in the HL group. Language processing is primarily associated with the left hemisphere, particularly Broca's area and Wernicke's area, but the right APFC is also involved in working memory, semantic monitoring, planning, and reasoning. Since the task required not only listening to and reading lips but also reproducing it exactly as heard and seen, the AO, VO, and AV conditions likely engaged right APFC in working memory processes, as participants had to listen and repeat the sentences. When it comes to those with HL, previous literature has shown greater activation in the frontal areas of the brain compared to those with NH, and that degraded speech processing leads to increased activation in this area (Berding et al., 2015; Eckert et al., 2009; Erb & Obleser, 2013). The activation of LAL observed in the HL group in VO condition indicates that visual information processing may be localized in LAL for those with HL. A decrease in activation observed in the medial PFC in the AV condition may be due to the auditory and visual information which may have reduced reliance on internally driven processing (Weaver & Richardson, 2009). In sum, findings of the study suggest the potential of using fNIRS at the PFC level to identify different brain activation patterns in speech understanding under AO, VO, and AV conditions, depending on the presence of HL. However, this pilot study has several limitations. First, the small sample size makes it difficult to generalize the results. Although participants subjectively reported no issues with cognition, no standardized cognitive measures were included to assess individuals' cognitive status. Considering previous research indicating that a greater degree of HL is associated with lower performance in working memory and executive function (Lin et al., 2011), individual differences in cognitive ability may have influenced the results. Incorporating validated cognitive tests, such as the Digit Span Test, allows for better control of potential cognitive confounds and isolation of the effects of HL on cortical activation. Besides, since the task involved both auditory and visual information, a more comprehensive neurophysiological mapping using multi-region fNIRS, or combining fNIRS with other techniques (i.e., EEG, fMRI) would be beneficial for capturing the full cortical dynamics of speech processing. Utilization of eye-tracking technology would provide objective data on gaze behavior, fixation patterns, and the use of facial cues during speech perception. In addition, in our study, the presentation level was fixed at 60 dBA to examine the intrinsic cortical activity of individuals with HL without the influence of their hearing devices. However, to enhance ecological validity, it is important to ensure audibility, particularly for those with HL. Subsequent studies with larger sample sizes and greater diversity in participant characteristics are needed. Including factors such as the degree and type of HL, etiology, aging effects, communication methods, and cognitive status would allow for subgroup comparisons, which could facilitate a deeper understanding of different patterns in multisensory integration in individuals with HL. For instance, Stropahl et al. (2015) examined evoked potential characteristics of cochlear implant users and NH listeners in face recognition. The results showed greater activation in the auditory cortex in cochlear implant users and the level of activation was positively related to their ability to perform lip reading. Brain activation patterns can also be measured at different time points in individuals wearing hearing aids or cochlear implants to investigate characteristics of brain plasticity (Seol et al., 2024; Stropahl et al., 2017; Stropahl et al., 2015). One of the notable advantages of fNIRS is its compatibility with cochlear implants. The fNIRS system operates with near-infrared light and is free from electromagnetic interference, which eliminates concerns about safety issues caused by metal or electronic materials and ensures no degradation in data quality or device malfunction when conducting fNIRS research with cochlear implant users. Taken together, while the characteristics of speech testing results for individuals with NH and HL may be similar across AO, VO, and AV conditions, different APFC activation patterns measured by fNIRS suggest that the brain areas involved in processing various sensory inputs during the communication process could vary depending on the presence of HL. Findings of the study highlight the need for further auditory research and the development of evaluation and rehabilitation tools that reflect these objective features.

Conclusion and Implications

fNIRS is a suitable technique for evaluating speech performance and the integration of sensory inputs in individuals with diverse hearing characteristics. Although both the NH and HL groups showed the highest speech performance in AV, where auditory and visual information are combined, fNIRS data showed differences in brain activation patterns depending on hearing status, even in AO and VO. Particularly, activation in the left anterior lateral PFC was observed in the HL group during visual information processing, suggesting the presence of compensatory neural mechanisms when auditory information is degraded due to HL. Currently, in clinical settings, there is a lack of assessments or rehabilitation tools that incorporate the integration of various sensory inputs such as AO, VO, and AV. Subjective measures, such as the listen-and-repeat task, are influenced by variability across examiners, patients, and test materials. Therefore, the use of objective measures is necessary to comprehensively evaluate communication ability and to support the development of individualized rehabilitation protocols tailored to the specific characteristics of each patient.

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Conflicting Interests

The authors declare no conflicts of interest.

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