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Research article

The effect of different visual feedback interfaces of music training games on speech rehabilitation in hearing-impaired children: An fNIRS study

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ABSTRACT

Singing plays a critical role in enhancing musicality, sound discrimination, and attention, and proves advantageous for speech rehabilitation in children with hearing impairments. Computer-based training games are well-suited to the learning behaviors of children, with substantial evidence suggesting that music training augments speech training capabilities in this demographic. Despite this, there is a lack of detailed exploration into the design of interactive online music training interfaces tailored for these needs. This study investigates brain activation changes using two visual feedback singing games, analyzed through functional near-infrared spectroscopy: a serious game (SG) and an entertainment game (EG) with visually enhanced feedback. It also assesses the efficacy of home-based music training software for speech rehabilitation.

Methods involved recording oxygenated hemoglobin concentration (Delta [HbO]) signals from the prefrontal cortex, motor cortex, occipital lobe, and temporal lobe in 21 children (average age: 9.3 ± 1.9 years) during two singing interface experiments. Subjects also completed the Intrinsic Motivation Inventory (IMI) questionnaire post-experiment.

Main results showed that brain regions, particularly the temporal lobe, exhibited stronger and more pronounced activation signals with the SG interface compared to the EG, suggesting that SG is more effective for speech system rehabilitation. The Intrinsic Motivation Scale results revealed higher acceptability for SG than for EG. This study provides insights into designing online speech rehabilitation products for children with hearing impairment, advocating for better interactive training methods from a neuroscience perspective.

Significance statement

Our research investigates the neural foundations of educational methodologies, assessing physiological responses to enhance our understanding of nervous system organization and function, which not only validates current practices but also informs the development of personalized educational strategies.

1. Introduction

A large body of literature has shown that musical training plays a positive role in improving rhythmic timbre and melodic contour recognition in people with hearing impairments [1–4]. There is a strong link between the development of speech and language skills in children and adolescents with hearing impairments and/or cochlear implants and musical activities, and that musical activities can improve and enhance the speech and language skills of children with hearing impairments [5].

Music training is both time-consuming and expensive, and the availability of qualified therapists is limited, which poses challenges for cochlear implant (CI) users, especially children, to access personalized attention and widespread training. However, the use of computers and mobile devices can greatly benefit these individuals by enabling music training anytime and anywhere. Over the past two decades, computers have emerged as popular platforms for hosting games, leading to the development of promising rehabilitation games [6]. Recent scientific studies have shown the effectiveness of computer-assisted speech training in enhancing speech recognition among CI users [7]. Additionally, moderate auditory training using speech training software at home has proven effective in improving speech comprehension [8] and recognition for CI users. These computer-based auditory training tools provide a valuable alternative or supplement to traditional auditory rehabilitation methods, and can be offered by clinicians to support

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patients' progress [7].

Augmented feedback, also known as extrinsic feedback, is a widely accepted strategy for accelerating motor skill learning. Augmented feedback provides information about motor performance or outcome that is presented by an external source, such as a trainer, therapist, or monitor [9,10] vision is often considered the most important perceptual modality in everyday life during interaction with the environment. At least in perceiving spatial information, vision dominates the other senses [11]. Most movements are cognitive masteries made on the basis of visually perceived information, and so have also been the most intensively studied modality in the context of augmented feedback. For example, visual feedback during movement is combined with its control to maintain stable movement [12]. Visual feedback aids in the rehabilitation of patients with cerebrovascular disease in order to change their posture [13].

Studies have shown that almost all groups of listeners are equally adept at detecting auditory speech with visual use of temporal cues in speech, whereas adults with normal hearing and children with hearing loss outperform children with normal hearing in extracting phonological information from visual signals and/or accessing phonological/vocabulary representations in long term memory using visual phonological information [14]. Therefore, enhanced feedback applications of vision should receive extra attention in computer-assisted speech training systems.

Serious games are developed primarily for educational or training purposes, rather than solely for entertainment, and are thought to incorporate a fun element that enhances motivation and reduces boredom during skill practice or learning sessions. Ongoing research is investigating the validity of these claims, with preliminary findings appearing promising.

Video games offer a cost-effective and accessible auditory training platform for hearing aid (HA) and cochlear implant (CI) users, providing motivation and incentives to fully utilize their devices. These games are integrated into a computer system that delves into various musical elements, including timbre, rhythm, mixing, and composition, offering an extensive, multi-component training experience tailored to each aspect of music. Despite its comprehensive nature, the system's complexity can pose challenges in usability. While this complexity may be manageable for adult CI users, it might be less suitable for less experienced users, such as children. Another work specifically aimed at children with CI: "Mobile Games and Auditory Training for Children with Cochlear Implants" (MOGAT) [15], but it has not been scientifically rigorous, and its effectiveness is unknown.

Grounded in the premise that musical training can significantly aid in the speech rehabilitation of children with hearing impairments, yet is prohibitively costly, our research also identifies a gap in previous studies regarding visual feedback mechanisms in online musical training for this demographic. Notably, there has been no dedicated examination of visual feedback in the context of online music training for children with hearing disabilities. To address this gap, we propose to employ two distinct interactive singing interfaces, designed with varying visual feedback methods. The objective is to analyze changes in brain activation patterns during the training process. Our aim is to uncover an optimal interactive model specifically tailored for online music training for children with hearing impairments. This endeavor not only seeks to resolve the challenges in speech rehabilitation for this group but also aspires to contribute valuable guidelines for the design of online products from a neuroscientific perspective, enhancing speech rehabilitation efforts for children with hearing disabilities.

In this study, we chose to study two interactive forms of music training games as shown in Fig. 1: Serious Game (SG), and Entertainment Game (EG) with visually-enhanced feedback. We used fNIRS to monitor the differences in the cerebral cortex of the same subjects while playing different interactive forms of music games.

In addition, all subjects were asked to fill out the Intrinsic Motivation Inventory (IMI) questionnaire after the experiment. We expected the following results:

1. With equivalent game rules and topic types, SG is more likely to activate the language system of the brain, especially the Wernicke area in the left hemisphere of the brain.
2. Analyzing the results of IMI scores, SG provided participants with higher intrinsic motivation. In addition, intrinsic motivation affects the activation state of certain brain regions.

If our findings are confirmed, they will guide the design of online speech rehabilitation games for children with hearing loss from a neuroscience perspective in the future.

2. Experimental material

2.1. Two different music interactive games

The Serious Game Interface (SG) shown in Fig. 1(a) and the Entertainment Interface (EG) with visually enhanced feedback shown in Fig. 1 (b) are both developed on a computer by Unity3D.The SG requires the user to mimic an audition and sing the song according to the pitch and melody of the audition, referring to the interface's short score and lyrics. Each lyrics corresponds to a structure, and a timer counts the time to determine the progress of the song, if the part of the lyrics is reached, the UI of the lyrics changes color.

In the EG, the user controls a small fish's vertical position on the interface by matching the pitch of their singing to visual prompts. The backend captures the user's vocal audio as a float array, standardizes this data, and maps it between 0 and 1. This float array then dictates the fish's movements up or down in real-time. The objective of the game is for the fish to eat as many squares as possible by accurately mimicking the song's tone and melody, enhancing the user's vocal accuracy.

Throughout the experiment, the Chinese song "I am a painter" was consistently used to maintain consistent variables. A ROG 3.5 mm

Fig. 1. Experimental interface design: (a) Serious game interface (SG) (b) Entertaining game interface with visually enhanced feedback (EG).

gaming headphone and a Lenovo Y9000P 2022 16-inch laptop were employed for audio input and display, respectively.

At the song's conclusion, both SG and EG calculated the number of notes per unit of time, counting a difference of an octave as one note. These notes were compiled into a sequence for comparison, determining the singing accuracy score.

2.2. Subjects

Out of the 28 subjects eligible to participate in this experiment, 2 subjects withdrew and 5 subjects provided abnormal data samples. Therefore, data were finally collected from 21 healthy young subjects (12 males and 9 females) and the basic information of the subjects is shown in Table 1.

All subjects met the following criteria: (a) normal or corrected visual acuity; (b) average hearing loss less than or equal to 25 dB for; (c) vocal cords that can produce sound normally; (d) no neurological disorders that would interfere with the experiment; (e) no structural brain abnormalities due to brain tumors and/or trauma.

The study was conducted at Shandong University. All participants' parents signed a written informed consent form. The experimental procedures were approved by the Human Ethics Committee of Shandong University and conformed to the ethical standards set out in the 1975 Declaration of Helsinki (revised in 2008).

3. Method

3.1. Experiment procedure

The experimental procedure consisted of three phases: 260 s experiment for SG, 260 s experiment for EG, and a 300 s dedicated to the survey research part as shown in Fig. 2 Participants were familiarized with the experimental setup through an introduction to the rules of the game and had the opportunity to try out the game before the main experiment. In order to control for potential order effects, the order of the SG and EG experiments was randomly assigned to ensure that there were no systematic effects on the results. Following the initial phase, participants completed the IMI questionnaire to measure and compare their intrinsic motivation during the two games.

After a 60-second break, participants played the game in a block paradigm, which consisted of a 70-second singing game followed by a 60-second break. All participants followed the researcher's "start singing" and "rest" cues. Each interactive game was repeated a total of two times. During the "start singing" period, participants focused on singing according to the interface cues, while the "relaxation" period emphasized maintaining a relaxed state. An 8-minute interval between experimental segments prevented fatigue errors as shown in Fig. 2.

3.2. Experimental equipment

In this experiment, we used fNIRS to measure functional brain activity in children. fNIRS has been shown to be a safe and effective non-invasive brain imaging method with stable signals and convenient experimental monitoring setups [14]. HbO signals are used as a parameter to explore neurological changes in the brain during fNIRS [15]. It has been observed that fNIRS indirectly records changes in cerebral neural activity by detecting changes in brain HBO signals and then calculating changes in cortical hemodynamics [16,17]. And it can be used to study the auditory function of patients with hearing loss [18]. Meanwhile, fNIRS has the potential to provide an objective measure of speech understanding [17].

It is minimally affected by the patient's movements and therefore has advantages over some other functional imaging techniques [19] can analyze both cortical sensory areas (e.g., visual, auditory) and integrated areas (e.g., prefrontal cortex). It can also spatially limit the localization of cortical activity to a depth of about 15 mm; another advantage is that it can be performed in a comfortable environment for children and requires a very short preparation time, making it more suitable for children.

In this study, we used the multichannel NIR system (Nirsmart, Danyang Huichuang Medical Devices Co., Ltd., China) previously employed to observe changes in HbO levels. Fig. 3(b) illustrates the spatial distribution of these channels across the four brain regions.

Table 1
Participants data.

Parameter	Basic information
Age(years old)	9.3 ± 1.9
Weight(kg)	31.25 ± 10.27
Gender	12males, 9females
Height(cm)	130.28 ± 8.23

*Mean ± standard deviation.

3.3. fNIRS data analysis

The fNIRS data collected from each participant during the SG and EG tasks were preprocessed [20]. This step was mainly performed using the NirSpark software developed by Danyang Huichuang Medical Devices Co. A generalised linear model (GLM) was used to examine the pre-processed time series data for HbO for each participant channel. Specifically, the GLM generates an optimal hemodynamic response function (HRF) for each experimental scenario and individual, and subsequently determines the degree of agreement between the observed experimental HRF values and the ideal values. By fitting real data collected from experiments to the appropriate experimental set up, GLM is able to estimate the activation coefficient beta value. This value represents the peak of the HRF function and indicates the level of experimentally induced cortical activation of the channel [20]. Typically, the beta value reflecting the peak HRF function is used for HRF prediction estimation of HbO signals to account for the level of channel cortical activation [21]. The set of beta values from each channel indicates cortical activation.

3.4. Statistical analysis

In the fNIRS test results section, we conducted a three-step statistical analysis on the HbO data. First, the Shapiro-Wilk test checked if the beta values from preprocessed HbO data followed a normal distribution. Second, we used a one-sample *t*-test to compare beta values between task conditions and baseline. Third, we differentiated significant differences between the two groups (SG and EG) using one-way repeated ANOVA for significance testing and applied the Bonferroni correction to adjust the significance levels of beta values. For the IMI questionnaire analysis, we used SPSS to process responses from 21 participants.

4. Result

4.1. Cortical activation analysis

HbO beta values for each channel were tested using ANOVA and Bonferroni correction for subjects using a serious gaming interface, an entertainment interface with visually enhanced feedback, to correct for the level of significance. The results of the HbO beta values showed that the brain channels that were statistically significant in the SG experiments were CH9, CH14, CH15, CH14, CH15, CH17, CH20, CH21 ($p < 0.05$). In the EG experiment, the statistically significant brain region channels were CH9, CH11, CH18, CH16, CH20 ($p < 0.05$). According to the data from the paired samples *t*-test, only the CH17($t = 2.192$, $p = 0.037$) in the TL region has a significant activation, while the other regions do not have a very significant change.

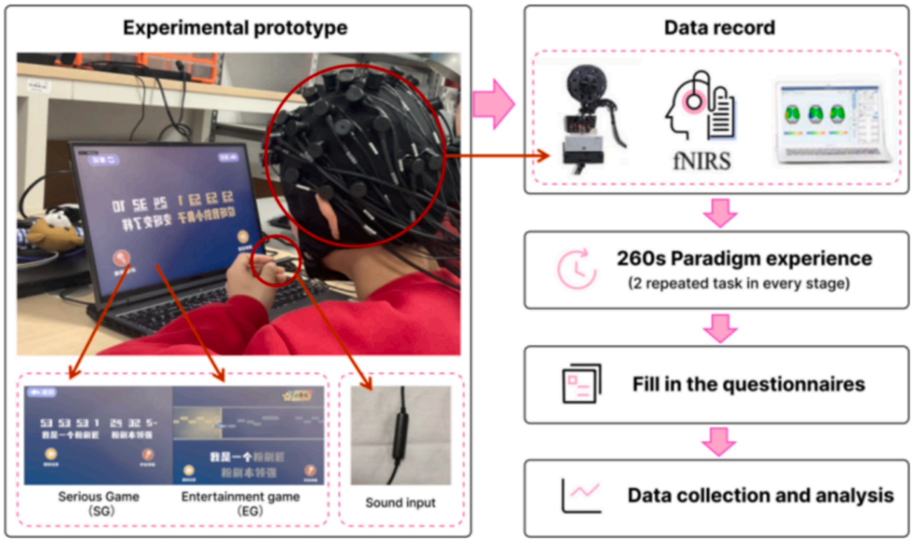

Fig. 2. Experimental prototype and process.

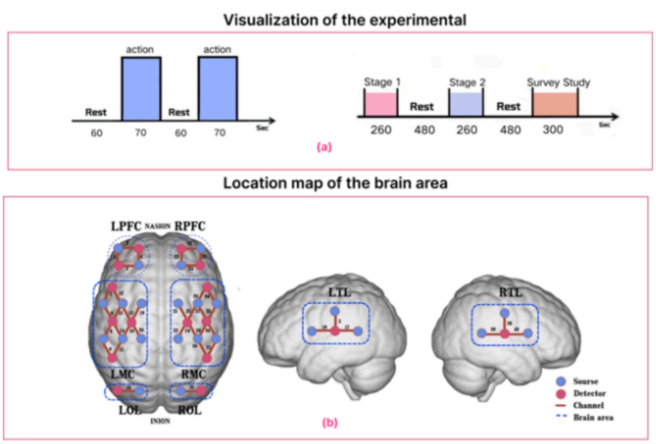

Fig. 3. Procedure: (a) visualization of the experimental Paradigm at each stage and flowchart of the entire experiment (b) Location map of the brain area.

4.2. *Cortical activation analysis*

The analyzed HbO beta values for the 40 channels are shown in Table 2. The highest value for R-OL was 0.725 and the lowest value for L-MC was −2.501. When using the recreational gaming interface with visually enhanced feedback, the highest value for R-PFC was 0.666 and the lowest value for L-PL was −2.098. Fig. 4 shows the cortical plots based on the analyzed HbO beta values corresponding to the two different music training interfaces. Red color indicates channels with higher beta values and blue color indicates channels with lower beta values. As seen in Fig. 4, brain regions were more active during training with SG, as more red and orange spots appeared in each region, especially in the prefrontal parietal layer and the left temporal lobe. In contrast, EG activated significantly fewer regions, activating only a small portion of the right parietal and posterior occipital lobes.Table 3..

4.3. *Correlation analysis of inter-cortical activation*

Pearson correlations based on HbObeta value analyses were performed for two different groups of brain regions using different music training interfaces and the results of the analyses are shown in Fig. 5 For the interface, significant correlations were found between the following channels: the L-PFC and L-TL, the R-PFC and L-PL. With moderate correlation: R-TL and L-PFC, L-TL and L-MC, L-TL and R-PL, L-PFC and R-TL, L-PFC and R-PFC.

For the EG training interface with visually enhanced feedback, in R-ROL and L-PFC, L-PFC and RTL, R-PFC and R-TL, R-OL and R-TL, R-MC and R-OL, L-MC and R-OL, Moderate correlation found at the interface.

Table 2
Comparison of HbO Beta values between SG and EG.

Channel number (CH)	Brain Area	Type of Game	HbO Beta Values		
			t	df	p
9	L-MC	SG	2.5761	21	**0.0156** *
		EG	2.8841	21	**0.0217** *
11	L-MC	SG	1.5983	21	0.0567
		EG	2.2173	21	**0.0349** *
14	L-MC	SG	2.2298	21	**0.0340** *
		EG	2.2945	21	0.0710
15	L-MC	SG	4.4438	21	**0.0156** *
		EG	3.1227	21	0.6891
16	L-MC	SG	2.9856	21	0.1095
		EG	2.7811	21	**0.0096** **
17	L-TL	SG	3.1220	21	**0.0041** **
		EG	2.8075	21	0.1876
20	L-MC	SG	2.2284	21	**0.0341** *
		EG	2.3159	21	**0.0281** *
21	R-MC	SG	2.0546	21	**0.0494** *
		EG	2.6267	21	0.3789
18	L-OL	SG	2.9364	21	0.4047
		EG	3.3106	21	**0.0026** **

* Moderate correlation ($p < 0.05$).
** High correlation ($p < 0.01$).

4.4. *Comparing activation between gender*

According to the HbObeta values, statistically significant channels for boys in the SG were CH9, CH14, CH15, CH17, CH20, CH21, and CH32. Eight channels were activated across the motor cortex (MC), temporal lobe (TL), and prefrontal cortex (PFC) regions, involving the right frontal, parietal, and left temporal lobes. In female participants using the SG, significant activation was found in CH15 and CH17, with two channels activated in the PFC and TL regions. For EG, significant channels for girls included CH10, CH15, CH16, and CH23, with activations in the TL, MC, and PFC regions. According to Fig. 6, boys showed significant activation only in the TL area during SG training, with no significant activation in EG. In contrast, girls exhibited significant activation in the TL area in both SG and EG, with more channels activated in

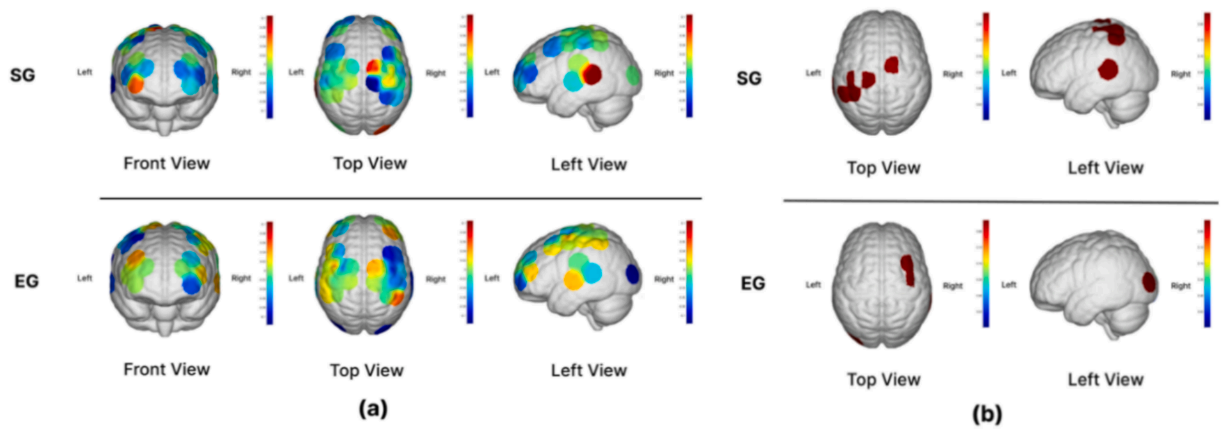

Fig. 4. (a) Comparison of the beta values of two training stage:Serious game (SG) and Entertainment game (EG) with visually enhanced feedback (b) The changes of value in baseline activation.

Table 3
Comparison of Hbo beta values between male and female in SG and EG.

Channel number (CH)	Brain Area	HbO Beta Values t	df	P	Type of Tasks	Gender
9	L-MC	3.3459	12	**0.0034****	SG	Male
		2.7538	9	0.3492		Female
14	L-MC	4.5175	12	**0.0002****	SG	Male
		2.8964	9	0.2876		Female
15	L-MC	5.1251	12	**0.0062****	SG	Male
		3.7493	9	**0.0056****		Female
17	L-TL	2.4446	12	**0.0244****	SG	Male
		2.9159	9	**0.0194***		Female
20	L-MC	2.7664	12	**0.0123***	SG	Male
		2.3978,	9	0.3875		Female
21	R-MC	2.2316	12	**0.0379***	SG	Male
		2.3987	9	0.1299		Female
32	R-PFC	3.1494	12	**0.0053****	SG	Male
		1.2986	9	0.3876		Female
10	L-TL	0.8838	12	0.6366	EG	Male
		2.8679	9	**0.0209***		Female
15	L-MC	3.5783	12	0.0740	EG	Male
		7.1572	9	**0.0077****		Female
16	L-MC	1.0809	12	0.3023	EG	Male
		4.8035	9	**0.0014****		Female
23	R-PFC	3.3586	12	0.4398	EG	Male
		3.5655	9	**0.0073****		Female

* Moderate correlation ($p < 0.05$).
** High correlation ($p < 0.01$).

EG.

4.5. *Results (of an investigation, poll)*

Fig. 7 The results show that the SG task elicited high value usefulness (mean = 6.33), high importance (mean = 6.26), moderate perceived (mean = 5.85) moderate interest/enjoyment (mean = 5.81), moderate tension (mean = 5.7), and relatively low stress tension (mean = 2.22).

In the EG task, participants experienced a high degree of importance (mean = 6.19), moderate value usefulness (mean = 5.81) moderate perceived (mean = 5.19) moderate interest/enjoyment (mean = 5.33), moderate tension (mean = 5.56), and relatively low stress tension (mean = 3.5).

5. Discussion

The analysis of the experimental data in this paper is based on the analysis and processing of beta values [22]. eta values can reflect changes in neural activity in the measured lateral cortex and are suitable for analysis and discussion. It has been shown that fNIRS can assess cortical activation using CI, which may help to predict the success of CI-assisted rehabilitation training [23].

Through single-sample t-analysis, it was found that training using the SG interface activated six channels, which were distributed in the L-MC, L-TL, and R-MC regions, with significant activation ($p < 0.01$) in the CH17, suggesting that the SG training had a significant activation effect on the TL-controlled language region. In contrast, training using the EG interface activated even fewer channels, only five, and concentrated in the L-MC region, CH16, CH8 also showed a strong correlation ($p < 0.01$), indicating that EG produces strong activation on vision when used, attracts excessive attention, and also produced a certain amount of stress and cognitive load. Whereas the paired t-tests of SG and EG showed that only the CH17 channel in the TL region produced significant differences. The TL region is particularly important for processing auditory signals [24]. A large body of evidence suggests that, regardless of the mode of sensory input, the TL region in the left hemisphere is specialized for language processing, [25–27] i.e. auditory input for verbal communication and visual input for speech reading or communication through sign language. Thus our results suggest that SG is more effective than EG for the brain's language areas with better activation.

Using the SG interface for training, correlations were found between a total of eight regions, with significant correlations found in the L-PFC and LTL, and the R-PFC and L-PL, especially in the L-PFC and LTL regions, which is in line with the previous study-Left Hemisphere Audiovisual Interaction Promotes CI's auditory recovery results [24,28]. The SG training interface was shown to promote speech recovery. In contrast, six moderate connections between regions were produced in the EG training interface, mostly focused on the right hemisphere of the brain, and did not produce significant connections.

We utilized the same song "I am a whitewasher" as the training song in our experiments, and used two different interface designs for the interaction visuals only. According to the experimental results, the significant activation areas of the EG were all concentrated in the L-MC region and did not activate the TL region, suggesting that the interface with visually enhanced feedback made the children focus more on the visual changes of the interface, and was less effective for speech rehabilitation training, despite singing out loud along with the interface. However, children wearing HA and CI are typically less literate and may be distracted from elements by visual changes [29,30]. This means that user interfaces designed for this particular group must be clear and straightforward in order to draw their attention to the most important objects. Therefore, simple interface designs such as SG are more suitable for children to train, especially for hearing-impaired children, where cognitive awareness loading should be minimized [31].

In addition, utilizing insights from neuroscience, our study examined gender differences in brain activity during various tasks by analyzing

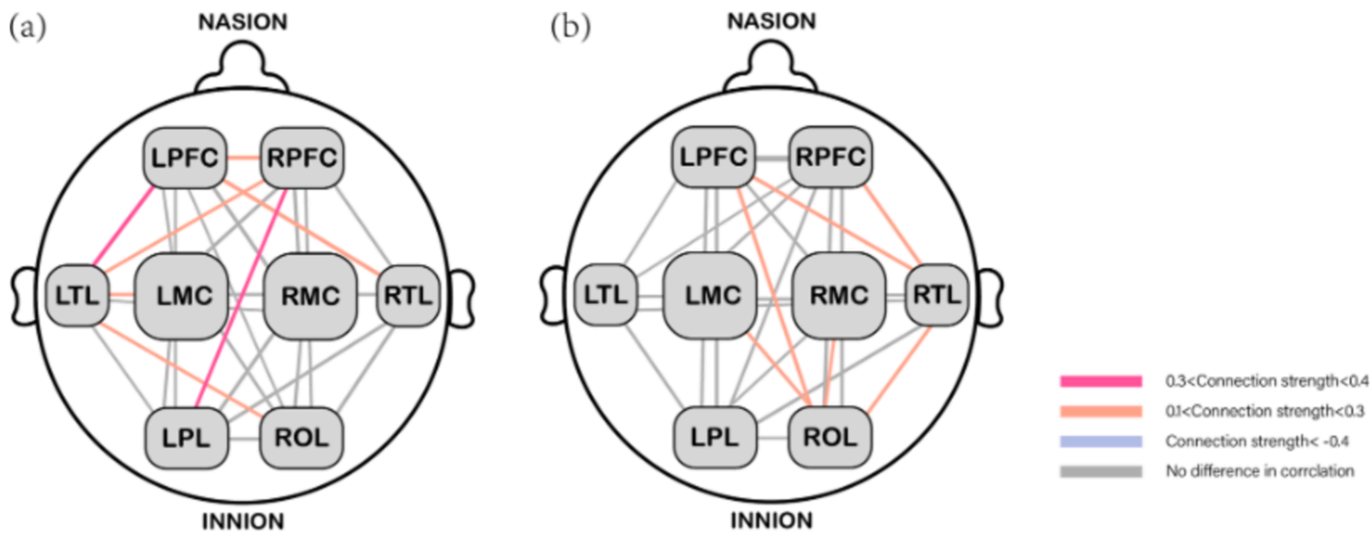

Fig. 5. Correlation analysis based on HbO 2 beta value of cortex: (a) Serious game (SG) training (b) Entertainment game (EG) training with visually enhanced feedback.

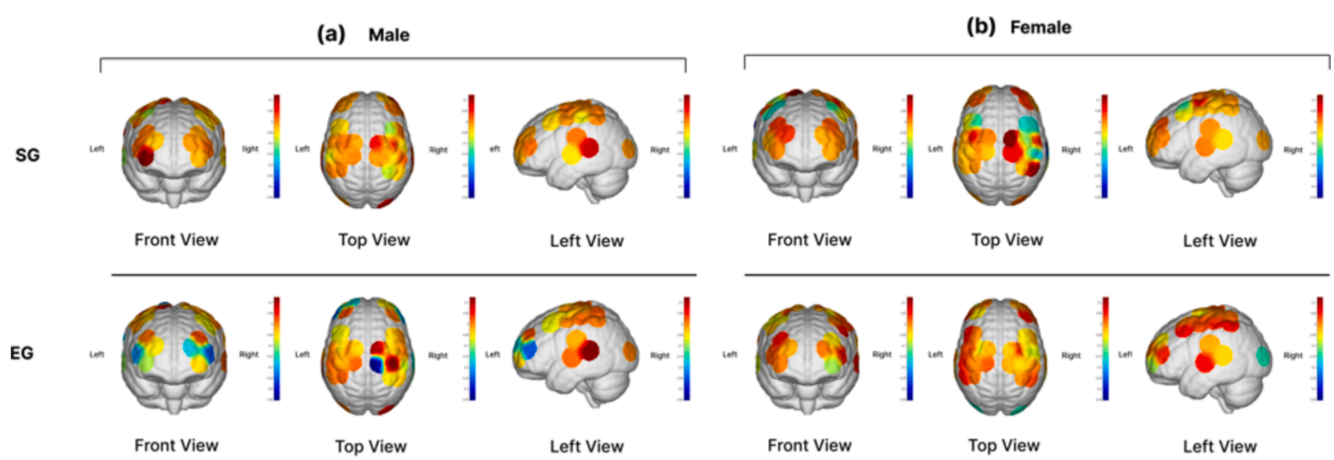

Fig. 6. (a) The brain activation state of the male in serious game and entertainment game with enhanced visual feedback (b) is the brain activation state of the female in serious game and entertainment game with enhanced visual feedback.

brain activations in same-gender groups engaged in different games. A one-sample *t*-test showed that boys activated eight channels in the motor cortex (MC), temporal lobe (TL), and prefrontal cortex (PFC), whereas girls activated four channels in these same areas. Further analysis of data from the serious game (SG) and entertainment game (EG) revealed that boys demonstrated significant activation in the TL exclusively during the SG, indicating heightened focus on this interface. In contrast, no significant activation was observed in the EG for boys. Girls exhibited significant TL activation in both SG and EG, with increased activation noted during the EG. These findings suggest that boys may be more responsive to the SG training model and more affected by visual modifications in the interface, while girls' brain activations appear less dependent on the type of game interface used.

Research has shown that motivated users significantly outperform unmotivated users when engaging in musical training activities [32]. Although both types of games elicited lower engagement pressure from participants, SG outperformed EG on all four dimensions, suggesting that SG better maintained motivation over time. Thus, the interface interactions used in SG are more suitable for the design of children's musical singing games than those used in EG.

Comparative analyses of the subjective scales revealed higher SG scores in both tasks, comparing them to the EG task on all dimensions. Elevated stress/tension scores were found in the EG task, but both games resulted in relatively low levels of stress. Thus, we assert that the SG task Enhanced perceptual abilities and elicited greater interest [33,34].

In this study, fNIRS was used to compare two different modes of visual feedback interaction in music training-serious game and entertainment game with visually enhanced feedback (i) motivate participants to actively complete a large number of music training tasks (ii) analyze cortical activation (iii) explore more age-specific interaction interface design options. This will help developers to screen for suitable options at the initial stage of the design process [35]. We also discussed the impact of different game approaches on the rehabilitation of children with hearing impairment. We found that all two training states had a positive impact on speech rehabilitation training; however, the SG interface training state was found to promote TL activation. According to the findings, subjects preferred the interaction mode of the serious game to the recreational game interface with visually enhanced feedback[36]. These findings will help developers to screen the best interaction methods for rehabilitation games during the conceptual phase of design and production.

In addition to providing insights into objective quantitative assessment, this study has practical implications. Computer-based auditory training tools (may be a useful alternative or supplement to clinician-

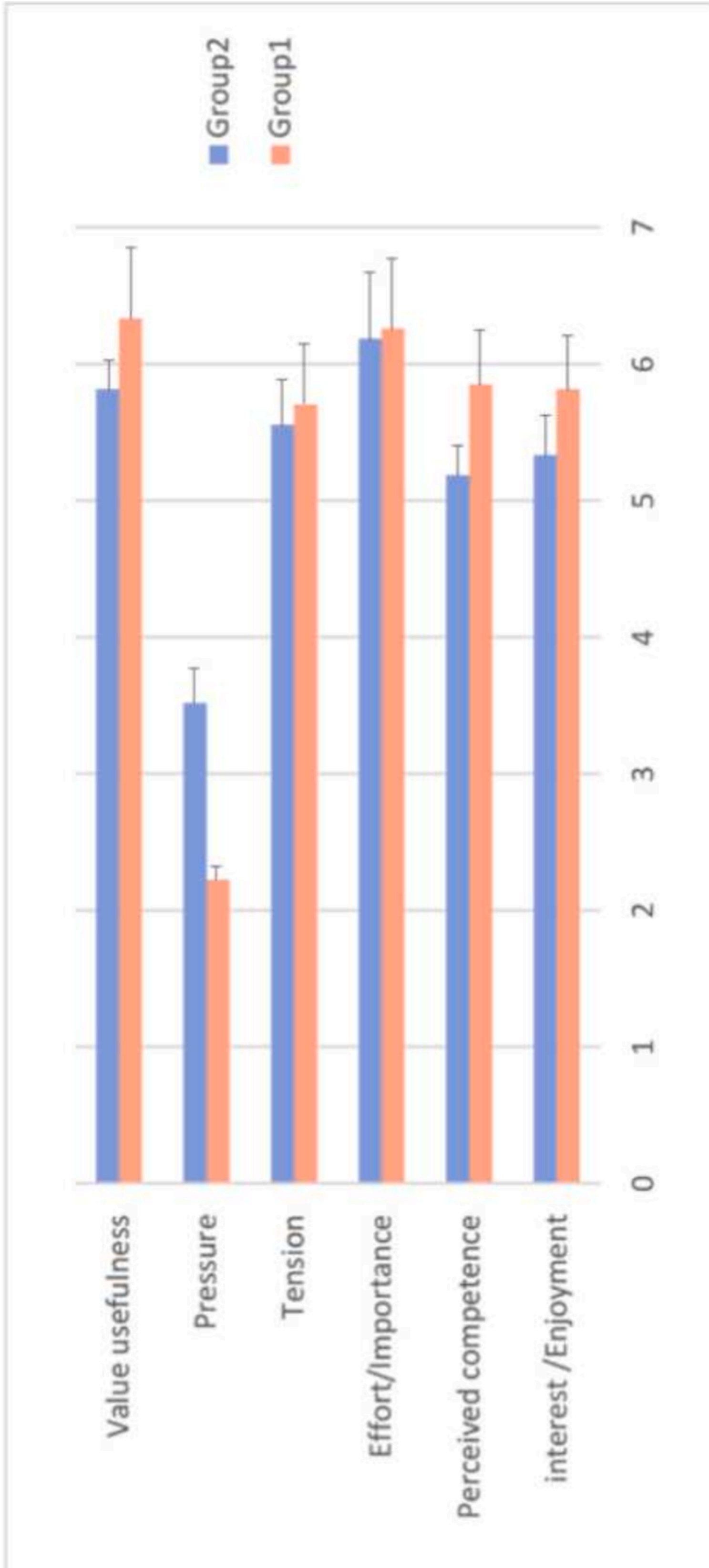

Fig. 7. IMI average comparison between SG and EG.

provided auditory rehabilitation. For children with speech disorders, such as those with autism and Down syndrome, speech rehabilitation training is a critical process for cognitive development [37]. Unfortunately, access to audiological rehabilitation services provided by hospitals and audiology clinics may be limited for many hearing autistic children due to time constraints, cost, and the patient's proximity to the rehabilitation site. Equipped with user-friendly speech training software, children with autism can easily perform self-directed hearing rehabilitation at home [38]; Therefore, the time and cost of site-specific hearing rehabilitation can be reduced. These findings provide important neuroscientific evidence for game designers, interaction designers [39] and software engineers. In addition, providing theoretical guidance for centralized trainers and trainees.

6. Conclusion

Existing research lacks a comprehensive discussion on brain activation resulting from different computer game rehabilitation methods. Utilizing near-infrared spectroscopy, we examined changes in cortical activity during rehabilitation training involving two distinct visual feedback interaction modes.

The results suggest that:

1. In terms of favoring the recovery of neuronal networks in the brain, SG produced stronger and more activation in brain regions compared to EG. In particular, significant differences emerged in the comparison of results in the TL region.
2. Meanwhile, in the left hemisphere we found a significant link between the L-PFC and LTL regions, suggesting that audiovisual produces a significant interaction that can promote auditory recovery in CI.
3. The EG interface with visual enhancement effect visually attracts too much attention during children's training, which is not conducive to speech rehabilitation training.
4. We also compared the genders and found that boys were more suitable for the SG training method, while girls did not show significant differences in the two tasks.

This study firstly provides a quantitative and objective process for evaluating different rehabilitation gaming methods, and secondly provides guidance for subsequent updating of the interaction model for designing speech rehabilitation products for children with hearing impairment. To this end, the results of the study will help developers to choose the best solution in the initial stages of speech rehabilitation product design.

This experiment explored two forms of visual interaction in a music training interface, represented by a serious game and a recreational game. Further investigation is needed to generalize the findings to other visual interaction designs for other training for children with hearing impairment. Participants were drawn from the general population of children, limiting instruction to specific groups such as children with hearing loss. This study only assessed the effects of a single music training session on the speech system and lacked insight into long-term effects. Future studies will delve deeper into specific populations and assess the long-term effects on the brain of various modes of visual interaction during speech rehabilitation training. In subsequent experiments, we intend to (i) recruit more hearing-impaired children (ii) comprehensively and meticulously study the effects of visual interaction changes on brain and neurological rehabilitation, and (iii) quantify feedback metrics of the stimuli. Since there is a certain amount of systematic interference in the process of using fNIRS, spatial regression will be used in subsequent experiments to avoid interference as much as possible.

CRediT authorship contribution statement

Song Hao: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Conceptualization. **Qiaoran Wang:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Yuhan Zhang:** Writing – original draft, Investigation. **Yibei Miao:** Data curation. **Yuxin Shan:** Formal analysis.

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Data availability

Data will be made available on request.

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