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Applying cross-modal plasticity principles in auditory training applications

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ABSTRACT

Research indicates that a significant number of individuals are in a suboptimal auditory health state, yet their auditory function can potentially be improved through auditory training. To raise awareness of auditory health issues, auditory training apps should provide effective yet accessible training methods alongside engaging mechanisms that motivate users to adopt and sustain auditory training habits, ultimately facilitating self-directed auditory health management. Current auditory training apps overlook the importance of user needs and motivation, as well as the relationship between the two, leading to low engagement and retention rates. We document the specific needs of both normal-hearing and mildly hearing-impaired users and analyze physiological data collected during auditory training tasks. Through lab experiment study, we provide quantitative evidence supporting the effectiveness of the auditory training method used in this study. The findings indicate that audiovisual-based auditory training contributes to improved auditory performance. Building on these insights, we develop an auditory training app prototype that integrates gamification and narrative design into the auditory training app prototype, and examine their impact on user motivation and engagement. Furthermore, based on the results, we propose design recommendations for future auditory training app development, emphasizing the need to align training effectiveness with user motivation and engagement strategies.

1. Introduction

World Health Organization (WHO) released its first world hearing report on March 3, 2021, calling on the relevant authorities to enable all people to have access to hearing health care (World Health Organization, 2021). According to the report, over 1.5 billion people worldwide are affected by hearing loss, of whom 430 million have moderate or severe hearing loss in better hearing ears. It is predicted that in the next 30 years, the number of people with hearing loss will increase by more than 1.5 times, and more than 700 million people may experience moderate or severe hearing loss. There are many factors contributing to hearing loss in the general public, such as ear infections, ototoxic drug abuse, and occupational noise exposure (Robler et al., 2022). Many reasons that affect hearing health are preventable. For example, WHO estimates that more than 1 billion young people are at risk of permanent hearing loss due to listening loud music or other media unconsciously for a long time, which shows that public attention to hearing health needs further improvement. Regarding the auditory health management for the general public, most of the interventions and treatments are aimed at people whose hearing ability already affects their normal lives (Fu and Galvin, 2007; Zhang et al., 2014; Sweetow and Sabes, 2007; Tuz et al., 2021). Furthermore, despite the existence of interventions that can be effective (Sweetow and Sabes, 2007), a considerable number of people in need do not have access to them: most people with a low level of hearing health live in a low-income environment where hearing health care services are not available (Anon., 2022; Planey, 2019).

Auditory training, sign language, and subtitles can also ensure that people with hearing loss have access to education and communication. In addition, there are various assistive strategies to help users with auditory tasks, such as reminding users when they are in noisy environments, assisting in conducting pure-tone auditory tests independently (Swann et al., 2012; Masalski and Krecicki, 2013; Corry et al., 2017), and utilizing wearable devices and apps for auditory training (Molini-Avejonas et al., 2015; McCaslin, 2020; Kim et al.,

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2021; Tuz et al., 2021; Sato et al., 2020; Chen et al., 2013; Ratnanather et al., 2021; Schumann et al., 2015). While various assistive strategies, including auditory training, sign language, subtitles, and wearable devices, offer valuable support for individuals with hearing loss, they often face challenges related to environmental and technological constraints (Murdin et al., 2022), leading to issues such as inconsistent effectiveness and limited accessibility (Potgieter et al., 2018). Among these assistive strategies, auditory training stands out as one of the most promising approaches for auditory health intervention due to its adaptability and potential for self-managed rehabilitation.

Auditory training is mainly divided into auditory discrimination training and auditory recognition training. Auditory discrimination is known as the ability to recognize individual sounds used in phonemes or sounds (Musiek et al., 2014). Since major auditory training tasks (e.g. similar phonemes or sounds discrimination Huang et al., 2022; Koprowska et al., 2023 and similar tones or pitches discrimination Wiener and Bradley, 2023) require distinguishing musical elements, auditory discrimination ability is crucial for users' performance in auditory tasks. Additionally, the hearing loss caused by the damage to sensory nerves is irreversible (Sataloff et al., 2006). Therefore, from the perspective of self-managed auditory health for those with mild hearing loss, training in auditory discrimination skills represents a valuable.

In the context of auditory discrimination training apps, significant issues exist for users with hearing loss, including a lack of diversity in training methods, monotony, ineffective feedback, and poor training outcomes (Huang et al., 2022; Irace et al., 2021). An overview of studies on auditory training apps including their pros and cons can be found in supplementary materials (Auditory training apps). For general public with mild hearing loss, the difficulty of auditory training is often mismatched with the users' capabilities (Samelli et al., 2017). The feedback provided by apps regarding training results and competency assessment is not sufficiently professional or accurate (Wildenbos et al., 2015; Sarkar et al., 2016). Moreover, there is a lack of quantification for user training progress, leading to a significant decrease in user trust in such apps and the development of a sense of rejection (Holliday et al., 2016). Consequently, this results in low user engagement and adherence to the apps, hindering the cultivation of a self-initiated approach to auditory health management. Finally, there are user experience issues, with current auditory training apps seen as using "boring" training methods (Kricos and McCarthy, 2007), low training effect (Moore and Amitay, 2007), and low usability or reliability (Paglialonga et al., 2015). The idea of gamification may hold promise to addressing the above issues by attracting user attention (Deterding et al., 2011; Goethe, 2019; Hallifax et al., 2019). By incorporating features such as milestones, progressive difficulty levels, and group creation, users can develop a sense of achievement and belonging. These game mechanisms could increase users' interest in the app, thus helping to overcome the feeling of boredom and low adherence, and enhancing intrinsic motivation (Tyack and Mekler, 2020). Additionally, mechanisms like points-based rewards and competitive leaderboards serve as external incentives (Anderson et al., 2013; Nicholson, 2015), driving user engagement through extrinsic motivation. In health-related apps, intrinsic and extrinsic motivations are often integrated to form a complementary system (Shin and Biocca, 2017; Schade et al., 2023), as seen in apps like Nike Run Club[1] and Fitbit.[2] This combined approach could effectively support users in transforming auditory training from a conscious effort into an unconscious, habitual health behavior. However, gamification has not been widely used in existing auditory training apps, despite its potential to support user engagement.

The overall goal of this article is to present our design process of developing an engaging auditory training app that takes into account users' needs and preferences, physiological metrics. Our approach is summarized in Fig. 1.

[1] https://www.nike.com/gb/nrc-app

[2] https://apps.apple.com/us/app/fitbit-health-fitness/id462638897

It outlines the key stages, including user research, auditory training app design, integration of gamification strategies, and evaluation through usability testing and user feedback. This process aims to enhance user motivation and engagement, ultimately promoting autonomous auditory health management. The key stages of the process are described in the following sections. Under the influence of sensory compensation mechanisms, even simple visual interventions can help users improve their hearing performance, also applies to healthy hearing people or those with mild hearing loss. In addition to visualizing the user's hearing training results, traceable hearing training records are also a means to help users systematically manage their hearing health.

2. Background

2.1. Auditory training

Different studies have explored different approaches to auditory training (e.g., PC-based language distinguishing Tuz et al., 2021, tablet-based words listening Sato et al., 2020 and handheld device based auditory training Chen et al., 2013), user attitudes towards mHealth apps for auditory training (Huang et al., 2022; Murdin et al., 2022), the benefits of such apps in enhancing the auditory performance of hearing aid and cochlear implant application (Schumann et al., 2015), and the benefits of sensory compensation interaction for communication (Rouger et al., 2012; Mushtaq et al., 2020; Chen et al., 2016; Lomber et al., 2010; Campbell and Sharma, 2016; Lyness et al., 2013). More recently, scholars have attempted to expand the research related to auditory training by combining sensory compensation mechanism and electrophysiological measurements, such as innovating the methods of auditory training, improving the auditory performance, and scientifically quantifying the results of auditory training (Ferguson and Henshaw, 2015; Brown et al., 2017; Gaeta et al., 2021; Yang et al., 2024). These studies indicate that traditional one-on-one auditory training methods are neither unique nor irreplaceable. This suggests that technology-driven, cross modal, and self-directed training may have a more extensive impact on the future of auditory training.

Over the past 20 years, music training has received growing attention as a model to improve hearing performance (Carcagno and Plack, 2011; Herholz and Zatorre, 2012; Zatorre, 2005). The main reason for its widespread use is that it covers the motor and visual elements in addition to its ability to meet auditory needs (Zatorre, 2005). Furthermore, the speed effects of music training on the cerebral cortex can be rapid, requiring only a few minutes of training to produce some real effects (Bangert et al., 2001). The sensory music task with adult non-musicians showed that fewer neural resources are needed to process the same information after training (Herholz and Zatorre, 2012). Some studies support the idea that long-term music learning experiences help improve auditory performance (Kishon-Rabin et al., 2001). Research has shown that specific auditory training is more beneficial than participants' prior music learning experiences, and these training effects can transfer to new tasks. This helps explain why musicians tend to perform better than non-musicians in auditory tasks (Spiegel and Watson, 1984).

Participants with music learning experience, especially musicians, present better performance in music tasks compared to non-musician (Spiegel and Watson, 1984; Rammsayer et al., 2012; Gagnon and Nicoladis, 2021). Some scholars (Moreno and Bidelman, 2014; Kraus and Chandrasekaran, 2010; Brown et al., 2017) have explained this phenomenon from the perspective of sensory compensation mechanism, affirming the promising application of music training in enhancing auditory abilities. However, the actual effectiveness of integrating music into auditory training remains unclear, and the potential influence of prior music learning experience on sensory compensation mechanisms also requires further investigation. The practical application of sensory compensation mechanisms is demonstrated in studies that use audio–visual stimuli to induce plastic changes in the cerebral cortex,

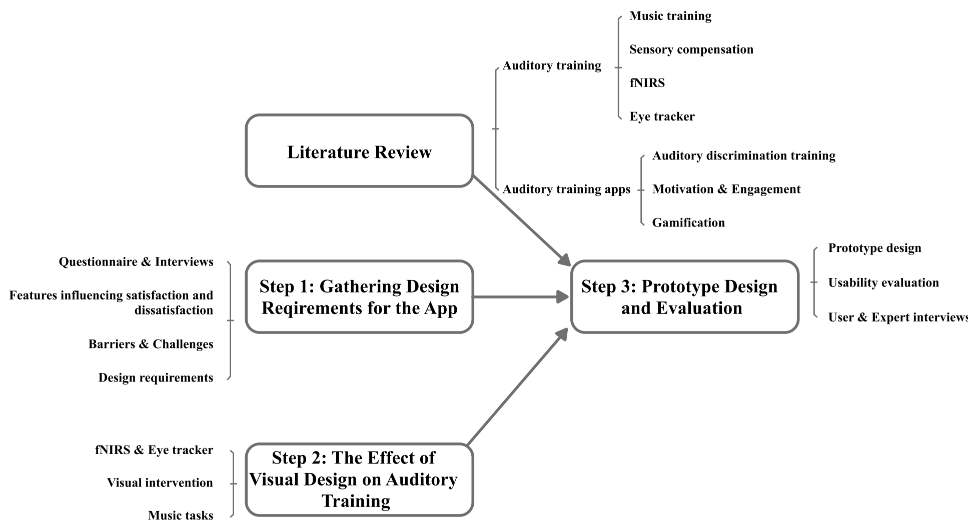

Fig. 1. The overview of our design process.

e.g., individuals with deafness or hearing impairments rely more on visual sensory compensation to mitigate auditory deficits (Gougoux et al., 2004; Lessard et al., 1998; Voss et al., 2004; Galimberti, 2021; Bavelier et al., 2006) and increased visual information input leads to enhanced auditory performance (Collignon et al., 2008; Voss and Zatorre, 2012; Dormal et al., 2016). Functional near-infrared spectroscopy (fNIRS) has been widely adopted for brain data collection due to its portability and resistance to interference (Wright et al., 2010; Zou et al., 2024). When combined with eye tracking, it enables a comprehensive observation of physiological changes in participants during audiovisual integration tasks (Proulx et al., 2014). Several studies using eye tracking in audiovisual tasks reveal that sensory compensation reduces cognitive load during task execution (Chen and Epps, 2014, 2020). Scholars indicated that the ability to modulate auditory sensitivity is strongest in response to audiovisual stimuli, confirming the superiority of audiovisual cross-modal plasticity connectivity (Cheng et al., 2020). In addition, this cortical plasticity is still prevalent in our adult brain, which lays the theoretical foundation for designing auditory training methods with generalizability for the general public (Buonomano and Merzenich, 1998; Draganski and May, 2008; Kerr et al., 2011; Heimler and Amedi, 2020). These findings provide a theoretical basis for auditory training in the task of detecting or discriminating sensory stimuli (Meijer, 1992; Recanzone et al., 1993; Bach-y Rita and W. Kercel, 2003; Wright and Zhang, 2009; Herholz and Zatorre, 2012; Abboud et al., 2014; Strait and Kraus, 2014; Irvine, 2018). In summary, effective auditory training serves as the intrinsic motivation for users to continue engaging in auditory training (Birk et al., 2016). From a long-term perspective, our goal is for users to adopt self-directed auditory training, ultimately leading to behavior change (Mekler et al., 2017). Therefore, in addition to fulfilling users' intrinsic motivation, it is essential to incorporate extrinsic motivational incentives, such as medals, ranking, socializing. Effectively leveraging extrinsic motivation can help users sustain their intrinsic motivation for auditory training, enabling them to better understand their own competence and build self-confidence. Numerous health-related apps incorporating gamification have already demonstrated the promising potential of this design approach in enhancing user engagement and promoting long-term behavior change (Paay et al., 2015; Zielinski et al., 2018).

2.2. Auditory training apps

Apps related to auditory mainly include auditory test apps and auditory training apps. Auditory test apps (such as Mimi Hearing test[3]) are used for screening hearing levels. However, they offer limited functionality. Auditory training apps (such as Tiger Speech[4]) offer more comprehensive features, aiming to assist users in managing auditory health by integrating diverse functionalities. The combination of hearing aid control, instructional videos, hearing tests, and auditory training has been proven to assist users with personalized needs and maximize their self-health management (Murdin et al., 2022). However, some technical issues (such as hearing aid connectivity and battery life) remain unresolved, and current auditory training methods in apps are relatively traditional (e.g., speech recognition tasks in noise). If users have experienced traditional auditory training methods and have not achieved the expected improvements in auditory performance, then the reliability of auditory training apps employing traditional methods may also be questioned by users. Certainly, some researchers have experimented with different auditory training materials to try to enhance their appeal or effectiveness, such as using dialogs or verbal materials (Ratnanather et al., 2021; Huang et al., 2022; Tuz et al., 2021; Ratnanather et al., 2021). However, despite the development of apps in multiple language versions, limitations due to pronunciation and language characteristics still exist. From a perspective of enhancing universality, different languages might become a major obstacle.

To make auditory training apps more engaging and motivational, gamification is clearly a better approach, but it is crucial to recognize that gamification elements used in non-game apps are essentially meant to stimulate user engagement rather than to actually achieve these accomplishments (Anderson et al., 2013; Deterding et al., 2011; Kusmierczyk and Gomez-Rodriguez, 2018). Consistent auditory training enhances users' auditory abilities, fulfilling their self-driven needs (Gooch et al., 2016; Yeckehzaare et al., 2020). As users progress to more challenging auditory training tasks, their competence needs may be met. When combined with gamification elements, this approach addresses users' intrinsic needs for autonomy, competence, and relatedness, thereby strengthening their intrinsic motivation (Rice, 2012; Peng et al., 2012; Deterding, 2014). In addition, extrinsic motivation can also enhance user performance (Cerasoli et al., 2014). External incentives include elements such as points and leaderboards. It is crucial to ensure that users perceive their actions as self-determined rather than controlled by external factors. On this basis, incentive elements that provide positive, visual feedback can help users accurately perceive and assess their own abilities, thereby strengthening their intrinsic motivation (Deci et al., 1999; Ryan and Deci, 2000). Additionally,

[3] https://mimi.io/mimi-hearing-test-app

[4] https://angelsound.tigerspeech.com/

thorough user research helps pinpoint the app's positioning by amplifying and meeting users' primary needs, and by organizing the app's hierarchical structure according to user expectations, which may helps increase user affinity for the app and reduce their learning costs. Unlike auditory training apps, auditory testing apps are more inclined towards testing auditory recognition abilities. Compared to the traditional gold standard pure-tone audiometry (PTA) (Organization et al., 1999) used in hospitals, mobile-based hearing test apps have low costs and potential for widespread use in low- and middle-income countries. Current research validates the feasibility of hearing test apps (Masalski and Krecicki, 2013), their reliability and effectiveness (Samelli et al., 2017; Thoidis et al., 2019). However, mobile-based pure-tone threshold tests present users with auditory levels only within the pure-tone category, lacking a more detailed assessment of auditory capabilities (e.g., discrimination, recognition). Furthermore, there's a lack of user research on the usability and learnability of hearing test apps.

Current research on auditory training and auditory training apps reveals several issues, primarily related to insufficient user intrinsic motivation. Auditory training methods often suffer from low or unclear effectiveness and a lack of engaging content, leading to reduced user trust and limited motivation to participate. Additionally, auditory training apps face challenges such as limited functionality and a failure to address user needs, resulting in inadequate extrinsic motivation. As a consequence, users struggle to transform conscious auditory training behaviors into unconscious health management habits. Therefore, the primary aim of our research was to design an auditory training app that facilitates effective auditory training while leveraging user research and gamification strategies to enhance users' intrinsic motivation and engagement in managing their auditory health. This approach seeks to shift auditory training from designer-driven interventions towards user-driven behavioral change (Paay et al., 2015).

In the following sections, we report a series of studies and activities conducted to design an efficient and universally applicable auditory training app. To address issues such as low usability and poor user adherence in auditory training apps, Step 1 involved user research to gather design requirements for an app. Step 2 focused on the development and validation of an auditory training method involving visual intervention. Finally, based on the results of the first two steps, we developed a prototype based on gamification design principles, verified its usability, and conducted an evaluation (Step 3). Ethical approval for all studies in this paper was granted by the Shandong University Ethics Committee. Written informed consent was obtained from all participants included in this study.

3. Step 1: Gathering design requirements for the app

In this section, we describe the results of a questionnaire study and interviews conducted with users and experts to gather the requirements to inform the development of an auditory training app.

3.1. Methods

3.1.1. Questionnaire

The questionnaire aimed to investigate users' auditory health, their opinions about the current auditory training methods and auditory apps, their willingness to accept auditory training, as well as their expectations for the auditory training. The questionnaire was distributed using WENJUANXING,[5] a free platform for conducting online questionnaire surveys, we posted a link to fill out the questionnaire directly to the participants, while other uninvited users of the platform were unable to participate or view the questionnaire (Ning et al., 2020; Shan et al., 2022), and is shown in supplementary materials. The questionnaire was live for 30 days. Once it closed, we summarized the results to identify the key trends, which then informed the interviews. Participants received no incentives.

3.1.2. Interviews

Based on the findings of the questionnaire study, we further carried out user and expert interviews. The aim of user interviews was to understand users' perception of auditory training; their participation in auditory training; subjective attitudes towards apps of auditory training; and their expectations and suggestions regarding apps of auditory training. The outline of our user interview is also shown in supplementary materials. The interviews lasted about 40 minutes each and were recorded to aid the analysis.

The purpose of the expert interview was to understand the general flow of the work carried out by the therapists; the training methods they used in the auditory training and the focus of the training; the difficulties in the work carried out by the therapist; and the perceptions and expectations about the auditory training prototype. The outline of our expert interview is shown in supplementary materials. The expert interviews lasted about 20 minutes each, and each participant received compensation equivalent to 10 USD. The interviews were recorded and summarized.

3.1.3. Participants and recruitment

We received a total of 79 valid questionnaire responses. Most of the participants (82.27%) were between 20–50 years old, mainly young and middle-aged users. Their education levels were distributed in graduate and undergraduate levels (25.32% and 54.43%, respectively). 63.29% of the participants reported having hearing loss to a certain extent (they chose "yes" to the question asking if they already had hearing loss or hearing impairment), and for most of them it was caused by bad habits and aging, e.g. listening to music loudly or wearing headphones/earbuds for long period.

The interviews participants were recruited from a network community of Xiaohongshu (also know as the Rednote[6]), they also completed the questionnaire that we mentioned above. We recruited three women aged between 20 and 30 years old. Two of them reported wearing hearing aids and cochlear implants respectively, and the third one did not use any wearable devices. The hearing level of all three users did not reach the level of accessible communication, but they were able to meet most of their daily needs. We also invited three experts with backgrounds related to auditory and visual training for this interview. Their expertise was: (1) medical, (2) otorhinolaryngology surgery, and (3) ophthalmology. All three participants were working in professionally related organizations and had rich theoretical and practical experiences of over 5 years (average = 10.3 years). Research shows that expert interviews in HCI often use small samples while providing valuable insights. Thus, interviewing three auditory therapists and three hearing-impaired individuals is reasonable and aligns with qualitative research standards (Franz et al., 2019).

3.1.4. Analysis

We used descriptive statistics to analyze issues such as classification information on users' hearing levels, causes of hearing loss, and subjective attitudes towards the auditory training apps. Users' attitudes towards the functional optimization of the auditory training apps and the most appealing features were counted using the composite scores of the options (calculation of the scores: average composite score of the options = ((Σ frequency $\times$ weight) / number of times the question was filled in). Additionally, we aimed to explore whether different user characteristics influence the most satisfying and dissatisfying features of hearing training apps. Since all the responses collected in our questionnaire are categorical variables, we chose to use SPSS to conduct a chi-square test on the survey results.

Both expert and user interviews were semi-structured. In this study, we used a thematic analysis organized into three rounds of team discussions to examine the data from interviews. The first round was

[5] https://www.wjx.cn/

[6] https://xiaohongshu.com

about sharing initial impressions and identifying potential themes from the transcripts that two of our authors had reviewed independently. This helped us gather a wide range of insights. In the second round, we worked together to combine these insights, merging similar themes and refining their definitions to ensure they were clear and closely related to the data. The final round involved a thorough review to reach agreement among our authors, making sure each theme was clearly defined and supported by enough evidence. This structured and collaborative process continued during work on this manuscript. It improved the reliability of our analysis and ensured that our findings accurately reflected the users and therapists' experiences and perceptions regarding the auditory training apps. Eventually, three themes were determined: *Experience with apps, Benefits of apps and auditory training, Barriers and challenges*.

3.2. Results

3.2.1. Questionnaire results

Features that influence users' satisfaction with auditory training apps.

Age The chi-square test indicated that user age significantly influenced their most satisfactory features of the auditory training app, $\chi^2 = 28.182, p = 0.005$. This finding suggests notable differences in user satisfaction across different age groups. Specifically, users under 20 years old primarily valued the app's ability to improve their hearing and expressed satisfaction with its training effectiveness. Users aged 20–29 were more likely to appreciate apps that are simple to use and have well-designed, streamlined functions. Those aged 30–39 showed a stronger preference for engaging training content, believing that an enjoyable experience helps them develop a long-term training habit. Users aged 40 and above found the training record function most beneficial, as they preferred apps that systematically track their progress, allowing for a more comprehensive understanding of their auditory training. These findings suggest that user needs vary by age. Younger users prioritize usability and training effectiveness, while older users place greater emphasis on structured training records and feedback mechanisms.

Hearing level The chi-square test indicated that users' hearing levels significantly influenced their most satisfying feature of the auditory training app, $\chi^2 = 32.214, p < 0.001$. This suggests that users with different hearing abilities have distinct preferences regarding the aspects of the app they find most satisfying. Specifically, users with better hearing ability (who rarely mishear or fail to hear information) were more likely to value the app's ease of use and the absence of redundant features. Users with a moderate hearing level (who often mishear or do not hear information) showed greater interest in the app's engaging and enjoyable aspects, believing that a fun experience helps them maintain their training. In contrast, users with poor hearing ability (who almost always mishear or do not hear information) primarily perceived the app as an essential tool for improving their auditory skills. These findings suggest that users with lower hearing levels prioritize training effectiveness, whereas those with better hearing abilities are more focused on ease of use and streamlined functionality.

Hearing intervention The chi-square test indicated that the type of auditory intervention users received significantly influenced their most satisfying feature of the auditory training app, $\chi^2 = 59.687, p < 0.001$. This suggests that users with different auditory intervention experiences have distinct preferences regarding the aspects of the app they find most satisfying. Specifically, users who wore hearing aids were more likely to appreciate the app for its simplicity of operation and refined features. Users who underwent cochlear implant surgery tended to recognize the engaging aspect of auditory training and felt that it helped them develop a habit of consistent practice. In contrast, users who participated in hearing training were more likely to believe that the app contributed to improving their hearing ability and were satisfied with their perceived progress. These findings highlight that different auditory interventions shape users' core needs and satisfaction with auditory training apps. Developers should consider optimizing app functionalities to cater to users with diverse intervention backgrounds, ultimately enhancing their overall experience and satisfaction.

Features that influence users' dissatisfaction with auditory training apps.

Age The chi-square test indicated a significant effect of age on users' least satisfactory feature of auditory training apps, $\chi^2 = 49.276, p < 0.001$, suggesting notable differences across age groups. Users under 20 were more likely to find the training method dull and unsustainable, indicating a preference for engaging and enjoyable training to maintain long-term motivation. Users aged 20–29 primarily perceived the interface as complex and difficult to navigate, highlighting higher expectations for usability and design. Users aged 30–39 provided varied feedback, with some expressing that they did not experience noticeable hearing improvement, suggesting a greater focus on training effectiveness. Users aged 40 and above were more likely to report that they struggled to recall previous training sessions and track their progress, indicating a preference for structured training records and feedback mechanisms. These findings suggest that younger users value engagement, while older users prioritize training traceability and effectiveness.

Hearing level The chi-square test showed a significant association between users' hearing levels and their least satisfactory feature of the auditory training apps, $\chi^2 = 70.068, p < 0.001$, indicating distinct dissatisfaction patterns among different hearing groups: Users with better hearing found the training method dull, emphasizing the need for more engaging content. Users with moderate hearing loss struggled with complex navigation, highlighting usability concerns. Users with severe hearing loss felt no improvement in their hearing, underscoring the demand for more effective training. These findings suggest that better-hearing users prioritize engagement, while those with greater hearing loss focus on training effectiveness.

Hearing intervention The chi-square test revealed a significant association between users' auditory intervention methods and their least satisfactory feature of the auditory training apps, $\chi^2 = 125.895, p < 0.001$, indicating notable differences in dissatisfaction across intervention groups. Hearing aid users found the training method dull and difficult to sustain, highlighting a need for more engaging and interactive content to support long-term use. Cochlear implant recipients reported complex navigation and difficulty locating features, suggesting higher expectations for interface usability. Users undergoing auditory training expressed a lack of perceived improvement in hearing ability, reflecting skepticism about its effectiveness and a preference for scientifically validated methods. Users without prior intervention struggled to recall previous training sessions and track progress, indicating a preference for structured training records and feedback. These findings suggest that auditory intervention history significantly shapes user dissatisfaction, emphasizing the need for tailored app design to accommodate different user experiences.

3.2.2. Experience with apps

The users' attitudes towards the training they previously had were complex. On the one had, they found the training was hard. First, it required human cost (such as support from family members), as described by one interview participant:

> "I have tried several auditory training apps, but I cannot use them independently and need assistance from my family" (Participant 1)

No survey respondent were unwilling to use auditory training apps despite their disadvantages. The main reason could be the low cost of apps, as explained by one participant from the interview:

> *"I stopped undergoing professional auditory training because of the high costs, but since most auditory training apps are free, I remain hopeful about using these apps for training"* (Participant 3)

Moreover, the interviews showed that therapists believed that the apps were only a supplement to in-person treatment and should not replace it:

"Professional training in a hospital definitely yields better results... but it requires patients' adherence, in terms of time, effort, and obviously money. In some cases, home-based self-training can consolidate the therapeutic effects and, of course, save patients' expenses" (Therapist 2).

Finally, among the 12 users who experienced the auditory training app, 50% (n = 6) of survey respondents were satisfied with the apps regarding improvement of their auditory performance. The chi-square test results indicate that these users are younger, have poorer hearing levels, and have undergone auditory training. Compared to those with higher hearing levels or no prior training, who prioritize engagement, they have a more pragmatic need for auditory training apps, focusing on actual hearing improvement. Participants listed several apps they used or were familiar with, such as Voibook or TigerSpeech. They appreciated several features such apps provide, such as training in the discrimination of similar syllables and sounds. As explained by one interview respondent:

"I used Voibook[7] at home, it helped me a lot, especially in terms of distinguishing words in daily life". (Participant 2)

3.2.3. Benefits of apps and auditory training

We identified therapists and users as the two key groups most relevant to auditory training and training apps. The app benefits them by reducing therapists' repetitive tasks and alleviating users' training-related anxiety and costs. Based on the interviews, therapists held positive attitudes towards the auditory training apps. They believed they could reduce their workload, had several benefits for the users and were a promising tool for supporting auditory training. In fact, Therapist 1 even admitted working on one such app:

"We have seen a surge in the number of home rehabilitation apps... Overall, the results have been quite good, and we are currently developing our own auditory training app in collaboration with research institutions" (Therapist 1).

Another benefit of apps for auditory training was a sense of relaxation it brought to users, even though this was not their main or intended function. One interview participant said:

"My hearing isn't good, so I'm reluctant to communicate with others, even doctors... Using the app at home allows me to practice without tension and with a more relaxed vibe" (Participant 3).

3.2.4. Barriers and challenges

We identified several barriers, including barriers to use (e.g., lack of independence, limited suitability, complexity), barriers to engagement (e.g., interruptive feedback, absence of immediate positive reinforcement, inadequate customization, uncomfortable environment), barriers to motivation (e.g., vicious cycle of low confidence, monotonous training methods, lack of stimulation and rewards).

Barriers to use. In our survey, among the 12 users who experienced the auditory training app, approximately 8.33% users (n = 1) reported dissatisfaction with complex operation in auditory training apps. The chi-square test results indicate that these users are younger, have a moderate hearing level, and have undergone cochlear implant surgery. This may be because they perceive auditory training apps as a supplementary rather than a primary means of improving hearing, leading to more focused and specific functional needs. Furthermore, there were issues with regards to suitability of the apps as different ones may focus on specific levels of impairment. For example, one interview participants said:

"The app I'm using could to some extent meet my needs, but it didn't help my friends with a different hearing lost level." (Participant 2)

Therapists held a similar opinion. They argued that, compared with apps, auditory training in hospital was far more personalized. One of therapists said:

"One advantage of coming to the hospital is that we can tailor training programs specifically for each patient's unique condition, which might be less targeted when using an app. So we suggest that auditory training apps should just focus on normal training instead of solving multi-target issues, such as trying to train both hearing impaired people and CI wearers" (Therapist 1)

The above indicates the importance of universality of an auditory training app. Overall, these barriers highlight the need for more accessible, user-friendly, and universal auditory training solutions that can cater to diverse user needs while promoting independent use.

Barriers to engagement. We implemented screening criteria in the questionnaire (e.g., whether participants had prior experience with auditory training apps) to obtain more accurate insights into user needs. While among the 14 users who experienced the auditory intervention, 71.43% of survey respondents (n = 10) indicated that auditory training was the most satisfactory intervention they had experienced, only 25% (n = 3) explicitly stated they were willing to continue using auditory training apps, with 75% (n = 9) remaining neutral. One of the issues was poor training efficiency. To help deal with it, the respondents expressed a desire for positive reinforcement:

"I look forward to receiving encouragement and affirmation when I perform well, but if I don't do well, I'd prefer to be informed after the training session so I don't feel anxious." (Participant 2)

Additionally, among the 12 users who experienced the auditory training app, 50% (n = 6) of users cited the monotony of training methods as their primary dissatisfaction. The chi-square test results indicate that these users are younger, have better hearing levels, and have experience using hearing aids. Their hearing level suggests that their need for auditory training is not as strong as that of users with poorer hearing. Thus, engaging auditory training may serve more as a motivational factor for this group. One participant from the interview noted:

"Listening to the same content repeatedly makes me feel bored and like I'm wasting time." (Participant 3)

Therapists suggested that maintaining the basic framework of offline auditory training certainly enhances users' trust in the app, but based on the premise that users already find offline training methods boring, grasping the line between innovation and maintaining credibility will be a challenge.

"breaking away from traditional auditory training methods and introducing novelty could motivate users to persist with training." (Therapist 2)

These findings highlight the importance of incorporating engaging and innovative training methods to spark users' curiosity. It is also crucial to provide timely positive feedback during the training and delay negative feedback until after the session, thereby boosting users' confidence and commitment to the training process.

Barriers to motivation. Surprisingly, among the 12 users who experienced the auditory training app, users were most concerned not with

[7] Voibook is an app for hearing impaired people, for details please visit www.voibook.com.

features like customized training or online consultations, but with more scientifically effective training methods, with 58.33% (n = 7) of survey respondents indicating this as their primary need. This was followed by a preference for more interesting training methods and simpler operations. One interviewed therapist noted:

> *"For trainees, immediate and noticeable improvements in auditory ability are their main motivation. However, the cost of time and money can impact their commitment to training. Game-like reward mechanisms may help users gain a sense of achievement, gradually fostering a habit of self-directed training."* (Therapist 2)

Participants also thought that features to support user engagement were just as important as efficient auditory training methods. This was illustrated by the following quote from one of the interview participants:

> *"I need something more motivating to help me stick with it."* (Participant 2)

Therefore, it is essential not only to ensure the efficiency of training methods but also to incorporate incentive mechanisms that sustain user motivation to engage in training consistently.

3.2.5. Design requirements

Through questionnaire and interview results reported above, we extracted users' needs and experts' advice for the development of auditory training apps. The auditory training app should follow the general training process (e.g., pre-training inquiry about auditory health, basic advice on training directions, and progression of training difficulty from easy to difficult). In the process of using the app, users should be given timely feedback on the operation, should be able use the app independently, the burden of the guardian should be minimized, users should be actively encouraged to use the app, and they should be able to build up confidence in using the app. At the same time, in order to break the vicious circle of low efficiency, low confidence and low motivation, the app should be able to improve the user's auditory ability, and combined with interesting forms of conducting, incentive mechanism to maintain the user's motivation to the training.

We identified the following design requirements that informed our design:

- R1: **Balancing effectiveness and interest in auditory training.** Younger users tend to quit using auditory training apps due to their dullness, while older users are most concerned about improving their auditory performance. Auditory training materials (e.g., music clips) and presentation formats (e.g., visual animations) might help us to balance the effectiveness of the training with the interest in it.
- R2: **Combine audio–visual elements.** Presenting auditory training materials in an audiovisual format leverages the advantages of sensory compensation mechanisms, enabling users to access additional sensory information while potentially enhancing their overall interaction experience.
- R3: **Support user engagement.** To help users familiarize themselves with the app as quickly as possible and stay engaged, provide a compelling narrative that will encourage them to return to the app. Narratives are a motivating component in auditory training apps and are believed to be helpful to increase user engagement (Tan et al., 2011). This approach aims to prevent the negative emotions often associated with traditional instructional guidance, thereby enhancing user engagement.
- R4: **Traceability of training data.** Generate similar training logs, traceable training reports, etc. for users, to meet the needs of older users to master their own training progress and training results.
- R5: **Dynamic incentive mechanisms.** More incentives, such as recording and displaying the user's achievements, and a breakthrough mode with medals or experience rewards, are needed to satisfy the needs of users who use the app as a supplemental tool. Detailed reports of training results and challenging training based on the user's ability to improve, to meet the needs of users who see the app as a primary tool to improve their hearing.

However, before proceeding to the design stage, we first needed to ensure that a combination of audio–visual elements would be an effective approach. A study that aimed to investigate it is described below. Moreover, since the previous music learning experience might influence the auditory training performance (see Section 2.1), we explored the effects of music learning experience on visual–audio elements based auditory training in the study described below.

4. Step 2: The effect of visual design on auditory training

Since the combination of audio–visual elements was one of the user needs we identified, we needed to check the effectiveness of this approach. Additionally, music learning experience has been found to affect performance in auditory tasks (Wu and Shih, 2021; Kishon-Rabin et al., 2001; Micheyl et al., 2006). Hence, the aims of this study was twofold: (1) to examine whether the integration of audio and visual materials could work for the public (hearing people or people with mild hearing loss), in terms of improving their auditory discrimination performance; and (2) to explore the influence of existing music learning experience of participants on their auditory discrimination performance.

4.1. Methods

In this study, participants with over 3 year systematic music learning experience are defined as musicians, and participants without any music learning experience are defined as non-musicians. The definition of musician and non-musician differs in current literature (e.g., 6 year-experience Agres et al., 2022 or 11 year-experience Turchet and Pauwels, 2021 for musicians), hence we use the Goldsmiths Musical Sophistication Index questionnaire (Gold-MSI) (Müllensiefen et al., 2014; Teng et al., 2021) to check if the difference exist between musicians' and non-musicians' music level and music learning experience. Gold-MSI has been widely used and was validated in various music related studies (e.g., Correia et al., 2023; Schaal et al., 2015; Rimmele et al., 2022). A significant multivariate effect was found, Wilks' Λ = .338, $F(7,32) = 8.964$, $p < .001$, partial $\eta^2 = .662$, suggesting a large effect on music learning experience. This indicates that defining the participants with 3 years systematic music learning experience as musicians is reasonable.

4.1.1. Study design

We adopted a 2 by 2 design in our experiment, with the music learning experience of participants (musicians vs. non-musicians) and form of auditory training (with visual intervention vs. without visual intervention) as independent variables. The dependent variables in this study were participants' auditory discrimination performance, their brain data, and their eye-movement data. Eventually, two study conditions were established:

- **C1:** Participants perform auditory training with visual intervention.
- **C2:** Participants perform auditory training without visual intervention.

We expected the following results in our experiment:

Fig. 2. Example of the visual intervention animation used in the experiment: the fluctuations and shape of the animation represents the loudness, the pitch and the timbre of music.

- **H1:** Compared to non-musicians, musicians have stronger cortical activation in temporal lobe during auditory training, as reflected by higher β changes in both conditions (C1 and C2). We raise this hypothesis in that musicians may show stronger cortical response to music (Kraus and Chandrasekaran, 2010).
- **H2:** Participants have lower cognitive load in auditory training tasks with visual intervention, as reflected by lower β values in prefrontal cortex (PFC) and lower blink frequencies in C1 than in C2. We raise this hypothesis in that the audio–visual presentation of information may reduce cognitive load (Cong et al., 2022).
- **H3:** The cognitive load of non-musicians decreases more from C2 to C1, compared to that of musicians. Auditory ability of non-musicians are lower than musicians, and similar to people with hearing loss, non-musicians may rely more on visual compensation to mitigate auditory deficits in daily auditory tasks (Gougoux et al., 2004; Lessard et al., 1998; Voss et al., 2004; Galimberti, 2021; Bavelier et al., 2006). Functionally, visual intervention may reduce cognitive burden of non-musicians during auditory discrimination task. In terms of familiarity, it might also be simpler for non-musicians to process audio and visual information simultaneously, as they might be more used to such information processing approach.
- **H4:** Regardless of music learning experience, participants perform better in auditory training with visual intervention, as reflected by higher correctness scores in C1 than in C2. Previous work had revealed that additional visual information input leads to enhanced auditory performance (Collignon et al., 2008; Voss and Zatorre, 2012; Dormal et al., 2016).
- **H5:** The performance of non-musicians would increase more from C2 to C1, compared to that of musicians. We raise this hypothesis for the same reason as the H3.

4.1.2. Participants and recruitment

Through poster advertisements and email invitations, we invited 40 students from Shandong University (average age = 22.6; 14 (35%) women; 20 (50%) musicians) to participate in this study. Participants who took part in this study were not related to those invited in Section 3. They were not hearing impaired and had normal or corrected vision. Sample sizes of 40 and under have been used in a number of similar studies (e.g. Unni et al., 2015; Vermeij et al., 2017; Soltanlou et al., 2022; Yu et al., 2022) and therefore was deemed sufficient. The study was approved by the Ethics Committee of Shandong University and was conducted according to the ethical standards of the 1975 Declaration of Helsinki (revised in 2008). All participants had no mental impairment, no hearing impairment, and all had normal visual acuity or corrected visual acuity.

4.1.3. Materials

Ten pure music pieces without any lyrics or vocals (including five from China) were selected as the *original music* for this study. To test the participants' auditory discrimination ability, we created additional 20 adaptations (2*10 original music) based on the melody and rhythm, which we refereed to as the *adapted music*. We randomly selected five *original music*, and animated the soundtrack curve of these music pieces by using the Adobe After Effects 2022. The soundtrack curves were drawn based on the contour lines of the audio waveform in Adobe After Effects. The audio waveform reflects the loudness, pitch, and timbre of the music. For example, in Fig. 2, the greater the fluctuations of the curve, the higher the loudness of the music; the denser the fluctuations, the higher the pitch; and the shape of the waves represents the timbre. A total of 30 music clips (10 *original* & 20 *adapted*) and five video clips were generated and recorded on the laboratory computer.

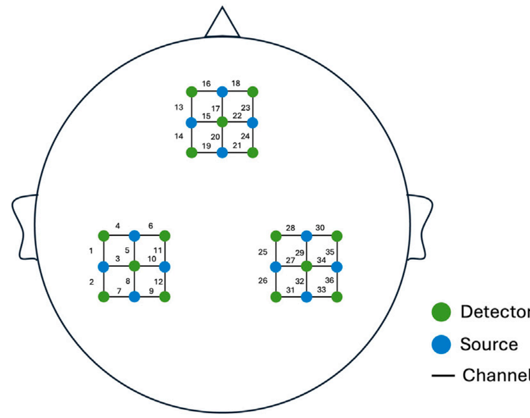

Fig. 3. Distribution of 36 channels in prefrontal cortex (PFC), left temporal lobe (LTL) and right temporal lobe (RTL). Each region consists 12 channels..

4.1.4. fNIRS and eye-movement data acquisition

To examine our hypotheses H1–H3, we measured participants' cortical activation and eye-movement. Changes in brain activation was measured using the functional near-infrared system NirSmart (Huitron, Danyang) (Ge et al., 2021; Li et al., 2021), with a sampling rate of 10 Hz. Thirty six channels formed of 27 probes (12 sources and 15 detectors) were distributed in prefrontal cortex (PFC) and temporal lobe, as shown in Fig. 3. The eye-movement was tracked using the Tobii-x2-30 eye tracker, with an resolution of 1080*1024, and a sampling frequency of 30 Hz. The brain and eye-movement data were tracked throughout the whole experiment.

4.1.5. Procedures

Upon arrival, participants were introduced to the experiment procedures and were asked to fill in the Gold-MSI questionnaire; according to the results of its music training sub-scale (Cronbach's α = .78), musicians had a significantly higher experience of music training than the non-musicians ($t = 6.718, p =< 0.001$). Before the experiment, fNIRS and eye-tracker were fitted and calibrated, and participants had approx. 90 seconds to get familiar with the tasks. Participants were asked to rest for 10 seconds at the beginning of the experiment to obtain fNIRS baseline.

The flow of C2 (pure sound) and C1 (video animations of the sound track presented) are shown in Figs. 4 and 5 respectively. For each study condition, participants were first required to listen to an original music A, and then were required to listen to three music pieces in turn (including one original music which is the correct answer and two adaptions of the original music). Immediately after listening to each piece of material music, the participants were required to answer whether the music was the same as the original music A. The duration of each music track was 20 seconds, and there was a 10 seconds interval between each track. For each condition of the experiment, we designed 5 items, and each item contained 4 pieces of music (1+3). So each part consists of 20 pieces of music (5*4). Taking C2 as an example, music A was the original music A, and the original music A, adaptation A1, and the adaptation A2 were randomly arranged to form the material music. During the experiment, participants were required to fix their eyes on a cross in the middle of the computer screen, to collect their eye-movement data.

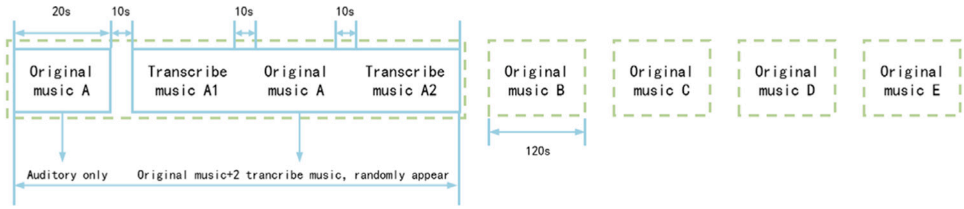

Fig. 4. The flow of study condition C2 (without visual intervention).

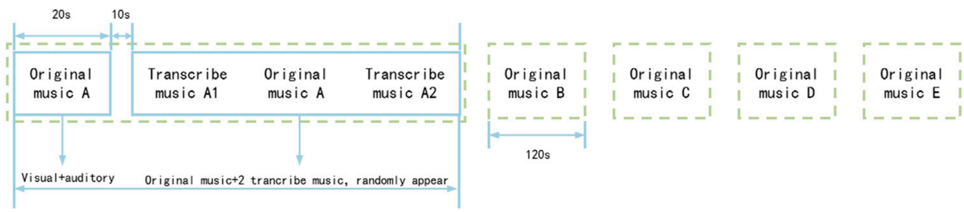

Fig. 5. The flow of study condition C1 (with visual intervention).

Table 1
T-test for β value for musicians and non-musicians between two conditions.

Brain regions	Channels	Musicians				Non-musicians			
		Mean	Standard	T	P	Mean	Standard	T	P
PFC	12	−0.0022	0.0126	−0.596	0.563	0.8824	0.1746	17.510	0.000*
LTL	12	0.0074	0.0188	1.364	0.200	0.3104	0.1656	6.492	0.000*
RTL	12	0.0013	0.0150	0.292	0.776	1.4527	0.1736	28.993	0.000*

Note PFC, prefrontal, LTL, left temporal lobe, RTL, right temporal lobe Paired samples t-test for both musicians and non-musicians.
* $p < 0.05$.

4.1.6. Data analysis

Brain data was pre-processed using the software Nirspark. The software handled the raw data through the following steps: (1) converting light intensity data into optical density (OD) data; (2) removing noise using a band-pass filter ranging from 0.01 Hz to 0.2 Hz; (3) calculating oxygenated hemoglobin (HbO) and de-oxygenated hemoglobin (HbR) through the modified Beer–Lambert Law; (4) HbO was further used to calculate the hemodynamic response function (HRF), based on which the β was generated by applying the generalized linear model (GLM). The β represents the activation of brain, the higher the β, the more activated the cortex (Ge et al., 2021; Yu et al., 2022).

As for eye-movement data, we selected blink frequency as eigenvalue, in that it was thought to be positively correlated to cognitive load. The correctness of the participants during experiment was recorded, and we refer to it as performance data. To examine our H1, the β value of temporal lobe of musicians in both conditions (C1 & C2) were compared with that of non-musicians. For H2, the β value of PFC and eye-movement data of participants in C1 and C2 was compared. Furthermore, the changes of β value of PFC and eye-movement data of musicians and musicians from C2 to C1 were compared to verify our H3. To check H4, the performance data of all participants in C1 was compared with that in C2. To examine our H5, the difference of participants' performance in the two conditions was first calculated, and an additional comparison was conducted between the calculated difference of non-musicians and musicians. Hence, a series of t-tests were conducted (using IBM SPSS) to make the comparisons.

4.2. Results

4.2.1. Cortical data

The difference of β values for participants between two conditions are shown in Table 1. For β value in PFC, significant difference ($t = 17.51, p = 0.000$) was only found among non-musicians between C2 (M = 0.0011, SD = 0.017) and C1 (M = −0.0002, SD = 0.014), indicating that non-musicians had significantly lower cognitive load when visual intervention was presented in auditory training.

The difference of β values between musicians and non-musicians in C1 and C2 are shown in Table 2. In C2, the β of musicians' PFC (M = −0.0009, SD = 0.018) was significantly lower ($t = 1.8, p = 0.04$) than that of the non-musicians (M = 0.0011, SD = 0.017). This indicated that without visual intervention, the cognitive load of musicians during auditory training was lower than that of non-musicians.

4.2.2. Eye movement data

The blink frequency of musicians in C1 (with visual intervention) (M = 345.15, SD = 203.281) was significantly higher (($t = 2.12, p = 0.047$)) than that in C2 (M = 265.75, SD = 153.472), while the blink frequency of non-musicians in C1 ((M = 253.1, SD = 182.829)) was significantly lower (($t = 2.158, p = 0.044$)) than that in C2 ((M = 306.4, SD = 182.156)). These results indicated that the visual intervention increased musicians' cognitive load during auditory training, while the non-musicians' cognitive load decreased in auditory training with visual stimuli. The differences of blink frequency are shown in Fig. 6.

4.2.3. Performance data

Compared to C2, the correctness of participants significant increased in C1. The details are shown in Table 3. Further, the correctness increase of musicians was smaller than that of non-musicians.

4.3. Conclusions

As our goal was to develop an auditory training app that could improve participants' auditory discrimination ability by implementing visual intervention, we conducted an experiment to (1) check the effectiveness of visual intervention in auditory training task, and (2) explore the impact of music learning experience on auditory training. No significant difference was found between the activation of musicians' temporal lobe and that of non-musicians; this did not support H1. The blink frequency and the β value in PFC of musicians increased when

Table 2
T-test for β values between musicians and non-musicians in C1 and C2.

Brain regions	Channels	C2				C1			
		Mean	Standard	T	P	Mean	Standard	T	P
PFC	12	−0.0101	−0.0056	1.8	0.040*	−0.0066	−0.0048	1.4	0.085
LTL	12	−0.0014	−0.0064	0.221	0.413	−0.0083	−0.0071	1.17	0.125
RTL	12	−0.0018	−0.0039	0.445	0.329	−0.0022	−0.0024	0.898	0.187

Note PFC, prefrontal, LTL, left temporal lobe, RTL, right temporal lobe Paired samples t-test for both musicians and non-musicians.
* $p < 0.05$.

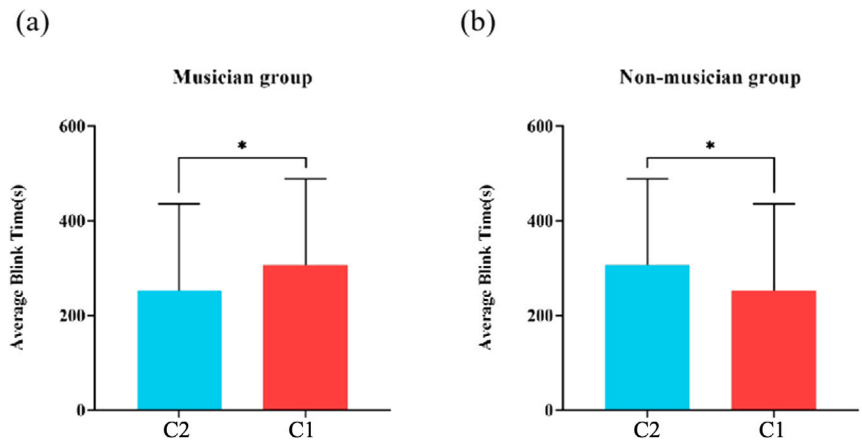

Fig. 6. Paired t-test for blink mean in two conditions: (a) Musicians; (b) Non-musicians.

Table 3
T-test for the change in correctness between the two conditions.

Correctness	Non-musicians				Musicians			
	Mean	Std	T value	P value	Mean	Std	T value	P value
	−4.8	2.0926	10.258	0.000*	−4.15	2.8887	−6.425	0.000*

Note The correctness of musicians and non-musicians in both conditions was tested by performing an intra-group paired samples t-test.
* $p < 0.05$.

visual stimuli was presented, while those of non-musicians decreased significantly. Only the non-musician part of these findings supported H2 and H3. Additionally, the performance data supported H4 and H5 — participants performed better with visual intervention, and the non-musicians' performance improved more with visual intervention. Overall, we found the audio–visual approach worked well, as it improved participants' performance (regardless of their music learning experience). Further, our findings suggested that additional visual intervention help reduce cognitive load of non-musicians. Since the form of visual intervention and music materials we selected were effective in our experiment, we further applied them in our auditory training app design.

5. Step 3: Prototype design and evaluation

5.1. Prototype design

Building on the findings from the first two steps, we identified that the most fundamental requirement for a hearing training app is to provide a clear and effective training outcome (as seen in R1 of design requirements), which directly drives users' intrinsic motivation. To achieve this, our app incorporates an audiovisual-integrated auditory training method, validated in Step 2. By leveraging the sensory compensation mechanism between auditory and visual modalities (as discussed in R2), we could positively influence user performance and enhances overall auditory skills. In our app, users listen to auditory stimuli (musical excerpts) while simultaneously viewing synchronized visual animations on the screen. To prevent users from conflating the purpose of auditory training (improving auditory performance) with the training process itself, we applied gamification strategies. Specifically, to align with R3, users are assigned the role of a "savior", and the training components are embedded within a narrative-driven experience. By downplaying the app's identity as a health-related tool, this approach fosters unconscious health behaviors, encouraging users to engage in self-directed auditory training.

To drive behavioral change and satisfy the R5 through the app, users must not only possess sufficient intrinsic motivation to generate self-drive but also receive extrinsic incentives to sustain and enhance this motivation. In this study, the extrinsic motivational elements incorporated into the app include a storyline, badges, points, leaderboards, friend circles, and friend competitions. These elements work together to maintain user engagement and encourage long-term participation in auditory training. In the storyline, users must continuously improve their skills and levels to ultimately confront and defeat the final boss (see Fig. 7).

The training is divided into main tasks and side tasks. **Main Tasks** consist of progressively challenging auditory training tasks. By completing main tasks, users earn experience points to level up, reflecting their growth in auditory skills. In the main task, a piece of music with synchronized visual animation is played first, as shown in Fig. 8.

Then, two variations with slight differences from the original and a replay of the original piece are randomly presented, forming a set of four tracks. After each playback, users have 30 seconds to identify the track identical to the first. Each training session consists of 15 sets,

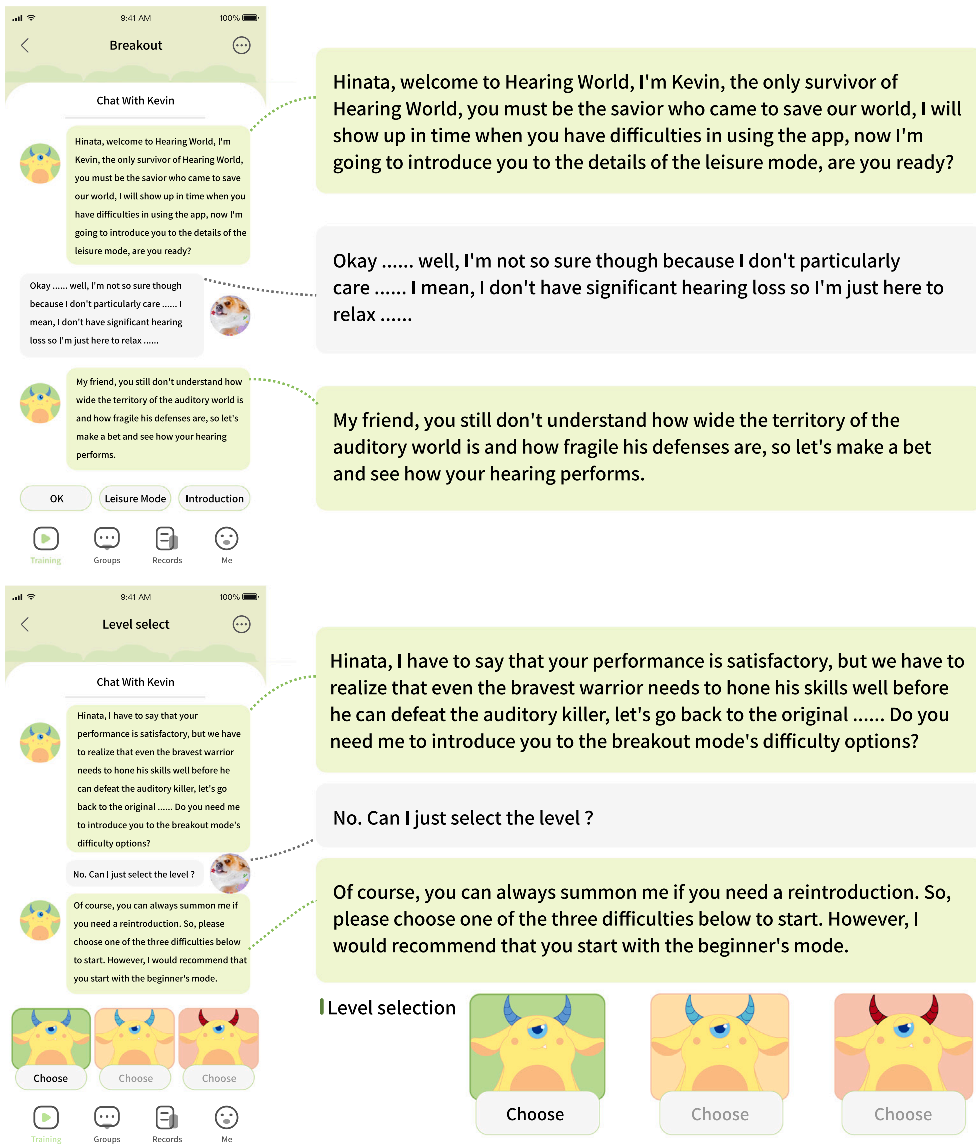

Fig. 7. The background of the auditory world's story line.

during which playback cannot be paused. Three incorrect selections result in failure, requiring a session restart with randomly refreshed music to prevent repetition. If the user successfully completes the session, they can advance to a higher difficulty level. At the same time, completed training sessions are displayed on a map. The interface features a small seedling that gradually grows into a tree as more sessions are completed (see Fig. 9).

As per R4 in the design requirements, progressive difficulty design helps maintain novelty and encourages user engagement. The map markers and seedling growth visually represent user effort and progress, allowing them to track their participation in auditory training. This fosters a sense of control over the app, strengthening intrinsic motivation and long-term retention.

Side Tasks are designed as more casual training activities, such as collecting story cards (see Fig. 10) and competing with friends. Through side quests, users can earn rewards like badges and points. Points can be exchanged for challenges to get story card fragments, gradually unveiling the world's background and enriching the narrative. Narrative design facilitates user engagement by intervening in cognitive and emotional processes (Legaard et al., 2020).

Badges, on the other hand, can grant special advantages, such as extra attempts during friend competitions or other side quests. This structure not only enhances users' intrinsic motivation and engagement (Tondello and Nacke, 2018; Lewis et al., 2016) through goal-oriented progression, but also integrates auditory training into an immersive, game-like experience. By incorporating a reward system, it may boost users' extrinsic motivation, complementary to its intrinsic drive. This synergy helps sustain users' motivation for auditory training, gradually transforming it into an unconscious, habitual health behavior. The purpose of providing various functional gameplay options in side tasks is to accommodate changes in user goals over time as they continue using the app. As usage time increases, users' needs and interests may evolve. Therefore, by introducing multiple objectives, the app helps sustain novelty, enhance long-term engagement, and reinforce user retention. The composition of side tasks, detailed descriptions, and design targets are shown in the Table 4.

To evaluate the early version of the prototype, we collected both quantitative and qualitative data. First, to assess its usability, we used System Usability Scale (Bangor et al., 2009) to determine whether the design was good enough to warrant a user study. Next, we asked participants to use the app for a few days and interviewed them about their experience. Both parts of the evaluation focused on usability and user experience. They are described below.

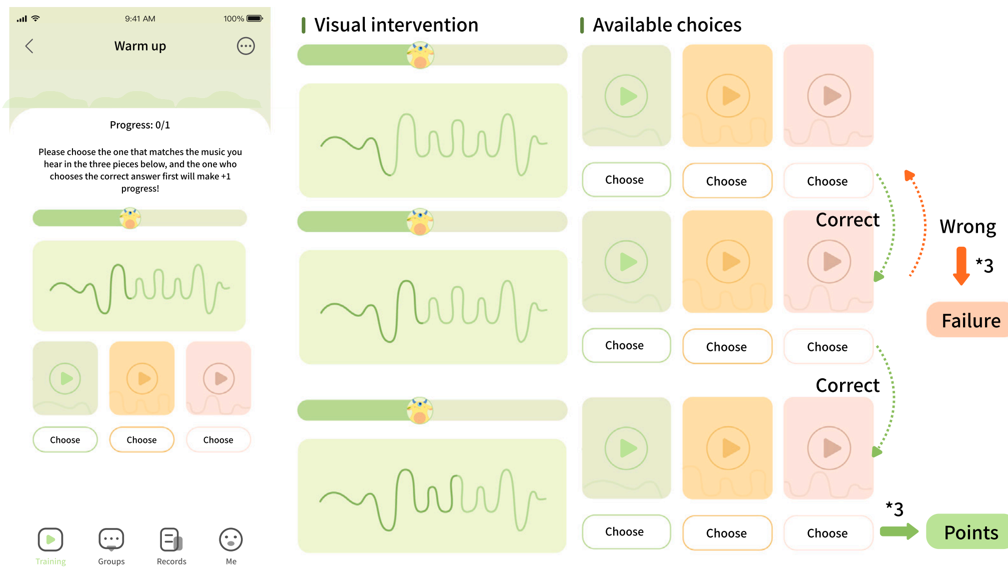

Fig. 8. The visual intervention in the app.

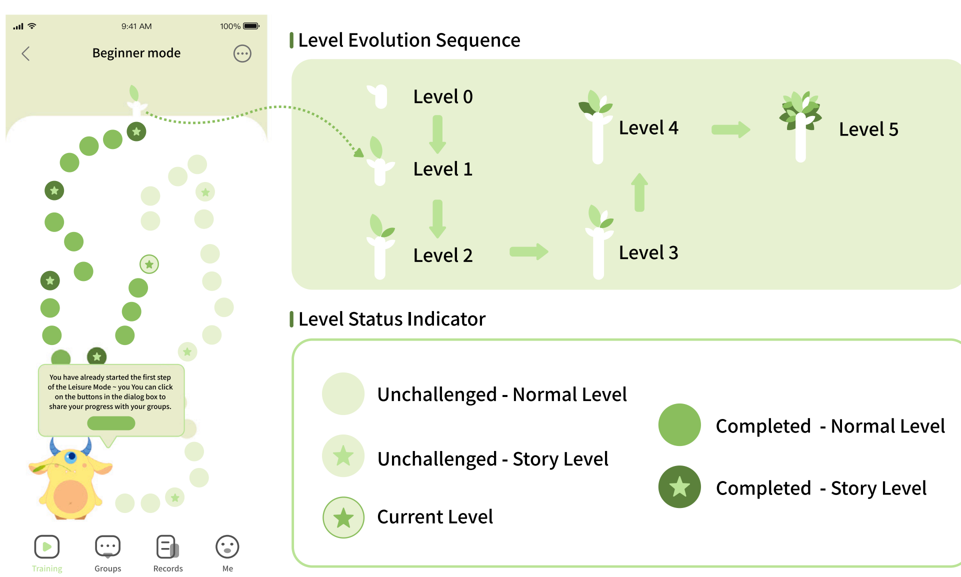

Fig. 9. The user progress map.

5.2. Usability evaluation

In this user evaluation session, we aimed to assess the usability of the prototype, focusing on whether its structural hierarchy was intuitive and its operational logic were clear.

5.2.1. Participants & recruitment

We recruited 17 graduate students majoring in design through poster advertisements and email invitations to design-related groups. Participants who took part in this study were not related to those recruited for the earlier studies. The participants included 10 women and 7 men, with an average age of 24 years old. All participants had normal or corrected-to-normal vision, no auditory or cognitive impairments, and no color blindness or color weakness.

5.2.2. Procedure

Users used our prototypes before participating in the evaluation. In case users' memories of the design and operational details were fuzzy, we played a 20 minutes video for users before the evaluation explaining the key features of the prototype. If participants had any questions about the prototype, we provided a more detailed demonstration and explanation. Each evaluation session lasted 45 minutes. At the end of the session they were asked to rate the prototype using the System Usability Scale (SUS) (Bangor et al., 2009; Tullis et al., 2004). We decided to use SUS (see supplementary materials) as it is free, has a few questions, and is less difficult for users to understand and operate. It is also suitable for the evaluation of websites and mobile apps.

5.2.3. Analysis

The SUS consists of a five-point scale with 10 questions, where odd numbers are positive statement items and even numbers are negative statement items. After participants completed the questionnaire, their scores were converted according to the principle of "original score – 1" for odd-numbered items and "5 – original score" for even-numbered items.

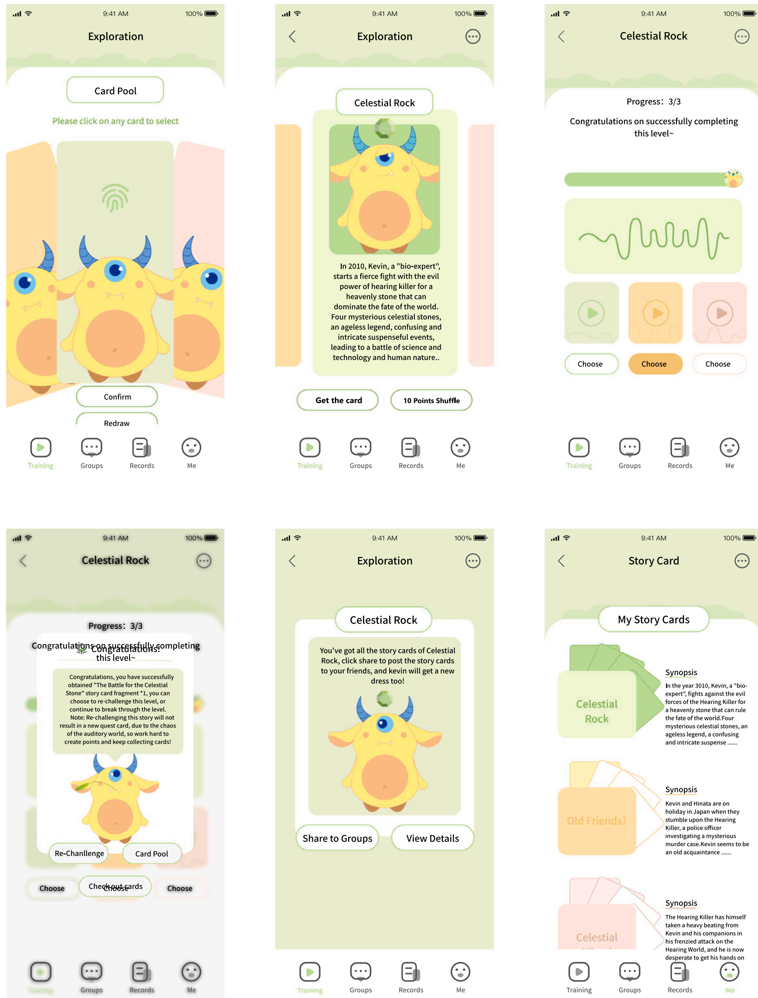

Fig. 10. The flow of story card.

5.2.4. Results & conclusion

The scale result showed that the usability score of the prototype was 85.48 and the ease of learning score was 79.41. The scores can be converted to a percentile grade for further interpretation, referring to the degree of usability of the evaluated app relative to other systems in the total database, with the usability scores in this evaluation corresponding to a grade of A+ and the ease of learning scores corresponding to a grade of A-. This indicates that based on user's using experience of the prototype and demonstration video, participants rated the auditory training prototype as having higher usability than about 97% of the apps and better ease of learning than 86% of the apps, suggesting that the design was clear and easy to understand. As the next step we decided to gather additional feedback.

5.3. Expert interviews

In addition to the usability test, we conducted interviews with users and experts. We asked participants to use the prototype we designed over a 3 day period, after which we conducted a semi-structured interview with each participant. Each interview lasted 40 minutes. The first few questions in both interview guides focused on users' opinions about app's key features. Next, we asked about potential further improvements and participants' general views on apps use for auditory health education and management. Though topics were the same, the questions for therapists and designers were slightly different; the interview guide can be found in supplementary materials.

5.3.1. Participants & recruitment

Since 80% of usability problems with a product could be uncovered by 4–5 participants (Rubin and Chisnell, 2008; Albert and Tullis, 2013; Faust et al., 2019), we invited therapists as domain experts and designers as expert user to provide feedback on the app. Four participants who took part in Step 1 agreed to test the prototype and be interviewed. This included two therapists (both men, average age 28 years, both employed in the Otology Department of the Provincial Hospital) and two designers (one man and one woman, average age 25, both with at least 5 years of interaction design experience). All participants received £20 Love2shop vouchers as compensation.

5.3.2. Analysis

We used a similar thematic analysis approach as described in Section 3.1.4, although in this case we were interested in understanding participants' opinions about specific aspects of the app (audio–visual materials, training method itself, gamification and fault tolerance features).

5.3.3. Results

The feedback from the participants was positive overall. All participants agreed that the Smartphone-based app use in auditory health education and management would help relieve the stressed hospital resources and improve public awareness of auditory health. Below, we present their opinions about the key aspects of the app.

Table 4
The composition, descriptions and design targets of side tasks.

Side task	Description	Target
1. Story Card	Upon entering the draw pool, users randomly obtain a story fragment related to the Auditory World's lore. Consecutive draws do not guarantee fragments from the same story. The first draw of the day is free. If unsatisfied, users can spend points to redraw. To claim a fragment, users must complete an auditory training session. Continuing to draw also requires points. If the training is incomplete or failed, 30% of the spent points are refunded - except for free draws, which offer no refunds.	Refine their character attributes, and instill a sense of responsibility and mission in their role.
2. Time - limited Challenge	The app periodically features real-world music for a limited time. Users can obtain these tracks by completing auditory training within the time frame. Each day, they have three challenge attempts. If they fail to succeed before the deadline, the track is moved to the "Unfinished Tracks" list in "My Music", awaiting its reappearance in a future challenge. Music earned through time - limited challenges can be used to initiate "Friend Duels" or shared in the "Groups".	Earn unique and rare rewards under time pressure, enhancing the user's sense of achievement.
3. Friend Duel	Users can invite friends from "Groups" or match with random players to participate in auditory training. This mode is a quick - response challenge, where the first to select the correct answer wins. Winners earn experience and points, while losers receive a smaller amount. Earned points and experience are recorded on the "leaderboard", generating daily, weekly, monthly, and yearly rankings for "Groups" players.	Enable users to build and expand their social connections, fostering a sense of community and engagement.
4. Medal Wall & Equipment Inventory & Title	Medals, equipment, and titles obtained through "main and side missions" can be viewed in the "Medal Wall", "Equipment Repository", and "My Titles" sections, respectively. During side tasks, users can equip only one medal, one piece of equipment, and one title. While not in training mode, they can freely equip or remove these items, but during training sessions, changes are not allowed. Medals, equipment, and titles provide special effects, such as an extra selection attempt, answer hints, or freezing the opponent's choice.	Boost engagement, personalize the experience, add strategic depth. And foster a sense of progression and identity in the app.

Impressions of audio–visual materials. All four participants expressed positive attitudes towards the materials used in the app. For example, one therapist we interviewed said they were impressed by the audio–visual aspects of the app:

> *"I quickly noticed the combination of visual and auditory materials, which is the biggest difference between this app and traditional auditory training methods. To my knowledge, there is a joint mechanism between images and sounds, involving responses in the occipital lobe and cortex, with a synergistic enhancement effect."* (Therapist 1)

Efficiency of the training method. Two users mentioned that this multimodal approach made their practice easier during the short study period. One said:

> *"I tried closing my eyes to determine if the music was the same, but it was harder to judge than by watching the animation, and mistakes occurred more frequently."* (Designer 2)

However, although participants acknowledged the positive effects of visual intervention, two experts still had reservations about the effectiveness of the app in clinical practice. They believed that the results of future professional clinical trials would be necessary and therefore may be more convincing. Nevertheless, both the experts and the users reported that they had felt the difference in the training methods we used, and they have expressed agreement with its effectiveness to varying degrees.

Benefits of gamification. All participants noticed the gamification logic used in the app and found this approach useful in promoting user engagement. For example, one therapist said:

> *"Patients would definitely find this app interesting and relaxing, compared to the traditional training in hospital, which seems much more serious".* (Therapist 2)

Two other users also agreed that they would be willing to use this app regularly as they found the storylines interesting. One user commented on the narrative design in our app:

> *"I understand the exploration mode is actually the combination of narrative design and gamification. Compared to the passive training I've done before, I really enjoy this approach in that stories in the app are attractive, I'm immersed and happy to put my efforts into the training process."* (Designer 1)

However, all participants had some concern regarding the individual differences and appropriateness of the narrative for different user groups, which could affect the overall effectiveness of the app:

> *"The story-line itself is interesting, but for those who don't like narrative, it might decrease their stickiness."* (Designer 2)

Fault tolerance helps maintain motivation. We were interested in the feedback on the fault tolerance feature as a tool for supporting the motivation. The feature received a positive feedback. All four participants reported finding themselves in a comfortable zone: they reported that they had felt challenged, but not too much. While the overall feedback was positive, one user suggested that the fault tolerance could have negative impact on the experience:

> *"As a patient, what I care most is the training results, and the visualization of training records* [so the] *results could be the biggest motivation for me to use the app."* (Designer 1)

Echoing this comment, one expert suggested we could increase the priority of displaying training records in our app. Nevertheless, overall, the usability evaluation results showed that our design successfully addresses barriers to use, engagement and motivation that were described earlier in Section 3.

6. Discussion

Auditory training apps, like most health-related apps, face the challenge of low user engagement and often rely on gamification to retain users. However, training effectiveness is the primary factor in building user trust. Ensuring that auditory training is effective is essential—only then does the goal of encouraging users to adopt auditory training as a long-term health behavior change become meaningful. To validate the effectiveness of our auditory training method, we conducted physiological assessments using biometric devices and analyzed user research data. Additionally, we explored ways to enhance the intrinsic appeal of training by integrating music and visual animations. Finally, we addressed engagement challenges through gamification, offering insights for the future design of auditory training apps. Below we discuss the insights gained from the whole design process.

6.1. The impact of gamified design elements on the auditory training app

6.1.1. Elements supporting intrinsic motivation

Through auditory training, users improve their auditory discrimination ability, which in turn enhances their capability to complete more challenging training tasks. This progression not only supports the transfer of acquired skills from the app to real-world applications, but also helps to maintain an optimal challenge level between training difficulty and user ability, sustaining user motivation (Denisova and Cairns, 2015; Gouveia et al., 2015; Lomas et al., 2017). For ambitious users, completing high skill-demanding tasks provides a greater sense of achievement (Hamari et al., 2016), which further reinforces their willingness to train, creating a positive feedback loop of accomplishment and motivation (Zichermann and Linder, 2010; Zichermann and Cunningham, 2011). In our study, users who have previously engaged in auditory training ranked effectiveness of training as their primary concern. Unlike instructional user guidance, we chose to build a complete world narrative with multiple storylines and a cartoon assistant, Kevin, who introduces each feature through storytelling when users first access them. This approach ensures users understand their actions and intentions organically, preventing the feeling of being controlled and fostering a sense of autonomy. Additionally, our app enables the users to track their training progress and achievements through the main task map, medals, and equipment from side tasks. Our finding suggested that the older users place the highest emphasis on the recording of training outcomes and the traceability of their progress ($p < .001$). Thus, our app enables the users to track their training progress and achievements through the main task map, medals, and equipment from side tasks. This not only provides a tangible representation of their abilities but also enhances their sense of control over the app and their auditory training journey (Saksono and Parker, 2024). Our results from the interview suggested that both therapist and users were both positive about the narrative design of our app. They labeled the world narrative as "*relaxing, less serious, immersive, attractive*". These findings aligned with the previous work (Bormann and Greitemeyer, 2015), which suggested the facilitation of immersion and an immersion-mediated enhancement of autonomy and relatedness need satisfaction through in-game storytelling. However, users' preference should be further considered in the future development of our app. The enjoyment of narrative design might not be influenced by user preference (Tondello et al., 2017).

Research suggests that the broader a user's social network within an app and the more it is tied to challenges and competition, the greater their time and effort investment (Suh et al., 2017; Saksono and Parker, 2024). To leverage this, we introduced a group feature where users can invite friends to join the app and share their achievements, such as story card collection progress, medals, and rankings. Friends can like and comment on these posts, fostering a sense of community. Additionally, daily, weekly, monthly, and yearly leaderboards track points and experience for both all users and friend-specific rankings, encouraging continued training to climb the ranks. As users invest time and effort in maintaining social connections and earning rewards, the growing sense of sunk cost makes it harder to abandon the app, reinforcing long-term engagement. In our study, however, we haven't had a chance to evaluate the social function of this app. Theocratically, elements such as leaderboards and the social connections could positively facilitate need satisfaction of competence and relatedness, and motivate users to keep using the app. Most users reported feeling confident while using the prototype in SUS scores, which may be attributed to the competence-related support it provides (Sailer et al., 2017).

6.1.2. Elements supporting extrinsic motivation

External rewards play a positive role in increasing extrinsic motivation and user engagement, though some studies suggest their effects are not always entirely beneficial. In this study, we treat rewards as a form of compensation and encouragement for positive user behavior. By linking active participation with rewards, we aim to help users build confidence in using the app and promote self-affirmation. The competitive and challenge-driven environment sustains users' focus and engagement, motivating them to pursue higher skills and achievements (Suh et al., 2017; Santhanam et al., 2016). The group feature fulfills users' social needs and sense of belonging. Interactive elements such as likes and comments provide feedback-based information, allowing users to gauge social expectations and respond through their actions (Siero et al., 1996). Research indicates that positive social feedback strengthens intrinsic motivation and encourages participation in more goal-oriented activities (Feng et al., 2018). In other words, enhanced social connection and recognition foster higher engagement (Hassan et al., 2019). Ultimately, we want users to improve their auditory abilities through the app while, under the influence of gamification design, gradually developing long-term health behaviors around auditory training. In addition to regulating intrinsic and extrinsic motivation, we incorporate narrative design into the gamified environment. By assigning users the role of "Savior", we immerse them in the story, enhancing their sense of engagement and exploration (Van Laer et al., 2014). This approach gives users meaning beyond the simple pursuit of goals and achievements (Dincelli and Chengalur-Smith, 2020). As users invest more time in various training objectives, their loyalty and engagement with the app naturally increase (Benitez et al., 2022), reinforcing sustained participation in auditory training. Both intrinsic and extrinsic motivation contribute to user engagement, as reflected not only in the results of user interviews but also in SUS scores, where most users expressed a strong willingness to continue using the prototype for auditory training. Despite their recognition of our gamification design, users raised a major concern about the high priority of gamified elements and storytelling in our app. They regarded the improvement in auditory discrimination ability as the first priority. Aligning with previous work (Abudiyab et al., 2022), our finding suggests that the visualization of auditory training records should be emphasized in our app to better motivate users.

6.2. Effectiveness of visual intervention in auditory training task

Due to the effects of music training and brain plasticity, musicians may show more increase in neural activity in music related tasks (Kraus and Chandrasekaran, 2010). This may suggest that individuals with prior learning experience have a natural advantage in auditory discrimination training tasks due to their stronger neural foundations. However, in our experiment in Step 2, previous musical training experience did not appear to have a significant effect on auditory cortex activation during training. The underlying neural mechanisms responsible for this phenomenon remain unclear. Nonetheless, extensive research has demonstrated that visual stimuli can compensate for auditory processing and activate the auditory cortex (e.g., Finney et al., 2001). This may indicate that visual intervention could have a stronger stimulating effect on users without prior musical training in auditory discrimination tasks.

In addition, with the introduction of visual stimuli, users with prior musical training experience appeared to exert more cognitive effort, although this effect was not statistically significant. This is reflected in an increase in their blinking frequency during the task, as well as a rise in HbO levels in the prefrontal cortex (PFC). A possible explanation for this phenomenon is increased cognitive load due to multi-modal processing (Erlandson et al., 2010). Musically trained individuals are accustomed to relying primarily on auditory processing, as their training has strengthened their ability to distinguish sounds without additional sensory input (Cohen et al., 2011). When visual stimuli are introduced, they may experience higher cognitive effort because they need to integrate both auditory and visual information, which they are not naturally inclined to do. In contrast, users without prior musical training experienced a significant reduction in cognitive load when visual stimuli were introduced during the auditory task. This suggests that visual input provided a compensatory effect, making it easier for them to process auditory information.

Overall, visual intervention had a more pronounced enhancement effect on users without prior musical training. With the introduction of visual stimuli: (1) Their auditory cortex activation showed no significant difference compared to users with musical training. (2) Their cognitive load decreased. (3) Their performance in the auditory discrimination task improved more significantly. However, visual intervention still benefited individuals with prior music learning experience, as their task performance also showed a notable improvement following the introduction of visual stimuli.

6.3. Design implications for auditory training apps

The previous sections have discussed the implementation and purpose of gamification in auditory training apps. Traditionally, these apps have focused solely on training, neglecting design considerations. However, their effectiveness in auditory training has been underwhelming, leading to low user trust and engagement. Through experiments and evaluations, we found that auditory training apps, having already lost a significant portion of user trust, should take a more cautious approach in validating their training methodologies. In terms of interface and structural design, greater emphasis should be placed on user-centered research and design innovation. Since auditory training requires repeated and sustained practice, users are prone to boredom with a monotonous interaction model. Therefore, maintaining extrinsic motivation through rewards and leaderboards is essential. While rewards are not the primary motivation for training, their incentive effect supports the continuation of intrinsic motivation. From a cognitive perspective, users gain a tangible understanding of their improved auditory abilities after training. Competition and challenges provide a sense of achievement and self-affirmation, while group interactions offer social feedback. This social reinforcement encourages users to respond positively to peer expectations, fostering higher participation and engagement. By addressing cognitive, emotional, and social participation aspects, auditory training apps can significantly enhance user engagement. Based on these findings, we propose the following design recommendations:

1. Gamification for Engagement: Introduce progressive difficulty, competitive elements, and reward systems to sustain motivation.
2. Narrative-Driven Training: Use interactive storytelling and role-based engagement to immerse users in training rather than presenting tasks as repetitive exercises.
3. Social Integration: Develop group features, interaction mechanisms, and ranking systems to enhance community engagement and peer motivation.
4. Visualized Progress Tracking: Provide clear performance indicators such as maps and achievement markers to reinforce self-recognition of progress.

6.4. Limitations and future work

This paper presents a design process and an initial evaluation of a prototype auditory training app. Our goal was to understand the hearing health management needs of normal-hearing and mildly hearing-impaired users, including their goals for auditory training, to assess the practical value of audiovisual-based auditory training methods in auditory training apps, and evaluate the prototype that integrates gamification and narrative design. The full evaluation of the complete app was out of scope of this paper. Future research should focus on the long-term effects on user training, as well as more in-depth evaluation of the positive effects of auditory training.

While the SUS is usually used immediately after the session in which users get familiar with the app, in our study, we decided to use it after a video demo session. We did so because we wanted to provide users with a more detailed demonstration and explanation, and to check for any immediate usability issues. This choice may has to some extent affected the effectiveness of the SUS measurement. Though we further conducted a user study to evaluate our app, more usability tests are needed in the future.

Through our work, we confirmed the positive impact of audiovisual-based music training on auditory performance and explored the potential of gamification and narrative design in motivating and sustaining user engagement. Although this study did not include a long-term evaluation, previous studies have shown that changes in cortical plasticity resulting from the influence of sensory compensatory mechanisms (audio–visual combined music training is used in this paper) can be preserved with continued consolidation (Alain et al., 2007; Naumer et al., 2009; Lee et al., 2020; Che et al., 2022).

7. Conclusion

This paper represents an initial exploration of integrating gamification and narrative design into auditory training apps to enhance user engagement and motivation, contributing towards facilitating behavioral change in auditory health. Existing auditory training apps primarily focus on training methodologies, but often overlook the impact of user experience design. They also lack validation of training effectiveness, resulting in low engagement and retention rates. To address this, we combined intrinsic and extrinsic motivation strategies to sustain user engagement and encourage long-term auditory training behavior. Our findings confirm that the effectiveness of auditory training remains the fundamental intrinsic motivator for users. The audiovisual-based training approach has a positive impact on auditory performance improvement. Furthermore, extrinsic motivational elements such as leaderboards and rewards can complement intrinsic motivation, encouraging continued engagement and facilitating a shift from passive task completion to self-directed behavior change. Additionally, integrating social interaction features in the app provides a solid foundation for fostering community engagement, further supporting user retention and long-term engagement. Our results provide both qualitative and quantitative evidence supporting the effectiveness of the proposed auditory training app prototype in improving auditory performance and user engagement. While further design refinements are needed to enhance usability, our findings suggest that combining effective auditory training methods with gamification elements could encourage sustained app usage by ensuring skill improvement in the app translates into real-world auditory performance gains. In conclusion, we demonstrate the potential of integrating audiovisual-based auditory training methods and gamification design in the field of auditory health.

CRediT authorship contribution statement

Qiqi Huang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Katarzyna Stawarz:** Writing – review & editing, Supervision. **Linqi Zhao:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Shuya Yang:** Resources, Data curation. **Wenyu Xie:** Resources, Data curation. **Fanghao Song:** Writing – original draft, Conceptualization. **Hantao Liu:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Qiqi Huang reports financial support was provided by China Scholarship Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhcs.2025.103570.

Data availability

The data that has been used is confidential.

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