Smartphone-Based Auditory Motion Stimulation for Hemispatial Neglect: Development and Usability Study

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Abstract

Background: Hemispatial neglect after stroke affects ~33% of acute stroke patients and is linked to poor recovery. Auditory motion stimulation, particularly using spatial cues, can enhance spatial awareness and may improve neglect outcomes.

Objective: To develop and assess “Neglect Radio,” a smartphone-based application delivering auditory motion stimulation, focusing on sound realism and usability.

Methods: Two auditory motion rendering methods—dynamic stereo volume control and standardised head-related transfer functions (HRTFs)—were implemented in a mobile app streaming public radio content. In an online study, 37 healthy volunteers rated the spatial realism (0–100 scale) of five audio sources in three conditions: static stereo, volume control motion, and HRTF-based motion. Independent samples t-tests compared realism scores. Ten participants tested the app for 15 minutes and completed the System Usability Scale (SUS).

Results: HRTF-based audio was rated significantly more realistic than volume control ($t = 3.722$, $p < .001$), and both motion conditions scored significantly higher than static stereo. The mean SUS score was 86.5, exceeding the 68-point threshold for above-average usability and rated “excellent.”

Conclusions: Neglect Radio delivers realistic spatial auditory motion and demonstrates excellent usability. This smartphone-based platform is scalable, accessible, and engaging, with the potential to complement hemispatial neglect rehabilitation. Clinical trials are needed to confirm efficacy and assess long-term use.

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Original Manuscript

Original Paper

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Abstract

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Keywords: hemispatial neglect; auditory motion stimulation; spatial audio; head-related transfer function; mobile health; neurorehabilitation; usability

Introduction

Visual neglect after stroke remains a major challenge in neurorehabilitation [1]. Patients with this attentional disorder fail to attend and respond to stimuli in their contralesional (often left) visual field despite having intact primary visual processing [2]. Notably, visuospatial neglect is very common after stroke, affecting roughly one-third of acute stroke patients [3]. Traditional rehabilitation methods focus on visual or sensorimotor interventions, yet recent research has increasingly explored multisensory stimulation, particularly auditory cues paired with visual stimuli, as a potential mechanism to compensate for visual deficits [4]. Auditory stimulation has been shown to influence spatial perception and attention, potentially activating compensatory neural pathways [5,6].

One of the foundational studies in this area, Bolognini et al. (2016) [7], examined the Sound-Induced Flash Illusion in patients with hemianopia and spatial neglect. Their findings indicated that auditory stimuli could enhance visual perception, reinforcing the role of multisensory integration in rehabilitation. Building on this, Zigiotto et al. (2021) [8] demonstrated that multisensory stimulation protocols improve spatial awareness in neglect patients. This highlights the concept that auditory signals can serve as external "anchors," enhancing awareness of the neglected visual space. An early study by Lewald et al. (2012) [9] provided direct evidence that passive auditory stimulation can enhance visual perception in patients. By exposing individuals to simple sound cues, they demonstrated significant improvements in spatial attention. Furthermore, music-based therapy using non-spatial auditory stimuli has shown positive effects on neglect [10-12] suggesting that even passive music can engage attention. Building on these insights, auditory motion stimulation can be viewed as music therapy enhanced with spatial cues.

Kaufmann et al. (2022) [13] conducted a proof-of-concept study showing that auditory motion stimulation reduces neglect symptoms after right-hemispheric stroke. They observed a short-term improvement in neglect severity after just a single session of auditory motion stimulation. Following this line of research, Geiser et al. (2025) [14] conducted a controlled study with 30 patients, reporting that a 3-week auditory motion stimulation training was feasible, well-tolerated, and led to significant improvements in neglect symptoms by discharge. In auditory motion stimulation, patients listen to music through headphones, with the music moving repeatedly at a constant speed from the ipsilesional toward the contralesional hemispace (or vice versa for right-sided neglect) [13,15]. While the clinical efficacy of auditory cueing has been demonstrated in prior studies [14], the present work focuses on the technical development and preliminary evaluation of a smartphone-based intervention.

This emerging evidence forms the motivation for a novel rehabilitation approach that we call Neglect Radio — a targeted auditory motion system designed to enhance spatial awareness and mitigate symptoms of visual neglect. Based on the pilot studies by Kaufmann et al. (2022) [13], Geiser et al. (2024) [15] and the controlled-group study of Geiser et al. (2025) [14], the objective of the present work was to develop a smartphone-based application that delivers auditory motion stimulation directly to patients. This 15–45-minute range was chosen to balance effective training time with patient endurance, reflecting typical therapy session lengths. Accordingly, this manuscript focuses on three key aspects: (1) generating the perceptual illusion of a moving sound source; (2) selecting appropriate and engaging audio content; and (3) implementing the *Neglect Radio* application for smartphone platforms.

We hypothesized that healthy listeners would perceive moving audio with spatial cues as more realistic than non-spatial audio. In particular, HRTF-based moving sound was expected to yield higher realism ratings than simple stereo panning, and both types of moving-sound stimuli were expected to be rated more realistic than static (non-moving) audio.

Methods

Creating the Illusion of a Moving Sound Source

In the Neglect Radio smartphone application, it is essential to generate a convincing auditory illusion of a sound source moving from right to left in patients with left-sided neglect (or left to right in patients with right-sided neglect, respectively). This effect can be achieved using two primary approaches:

1. Dynamic Volume Control of Stereo Channels:

One of the most straightforward methods for simulating movement involves dynamically adjusting the volume levels of the right and left stereo channels. By gradually decreasing the volume on one side while increasing it on the other, the perception of motion can be effectively induced. This approach relies on principles of binaural hearing, where the human auditory system interprets volume differences between both ears as an indication of sound source direction. Relevant studies on binaural hearing, such as the one by Blauert (1997) [16], emphasize the importance of interaural level differences in spatial hearing. Dynamic volume control is most effective for higher-frequency sounds, where the head acts as an acoustic shadow, enhancing the perception of lateral movement. Additionally, previous implementations in psychoacoustic research have demonstrated that smooth transitions in volume control significantly enhance the illusion of motion [17].

2. Simulation of a Virtual Sound Source Using Head-Related Transfer Functions (HRTFs):

HRTFs describe how sound waves interact with the human anatomy, specifically the shape of the outer ear, head, and shoulders, before reaching the eardrum. By filtering the audio signal through individualized HRTFs, a highly realistic perception of spatial movement can be created. Research by Wightman and Kistler (1989) [18] has shown that HRTFs are well-suited for externalizing virtual sound sources, making them appear to originate from specific points in space. Further studies (Begault, 1994) [19] have demonstrated that individualized HRTFs improve localization accuracy and enhance listener immersion. Implementing HRTFs in real-time requires computational processing, but modern advancements in digital signal processing allow for efficient real-time rendering of spatialized audio.

Both methods offer unique advantages and challenges. While the volume control method is computationally simple and widely supported by standard stereo playback systems, it lacks the spatial depth provided by HRTF-based approaches. HRTF simulation, on the other hand, provides a more immersive experience, but requires individualized filtering and additional processing power. The choice of method depends on the application context. For scenarios in which computational resources are limited, the interaural level differences method offers a practical solution. In contrast, applications demanding high spatial realism, such as virtual reality or advanced auditory displays, benefit from HRTF-based rendering. In both cases, the use of headphones remains essential to deliver separate signals to each ear and produce a convincing spatial illusion.

However, individualized HRTFs are impractical for scalable implementations in neglect therapy due to their complexity and user-specific requirements. This raises the practical question as to which method—volume control or standardized HRTFs—is more appropriate for therapeutic use. More specifically, does the HRTF-based method significantly enhance the perception of auditory motion compared to the simpler volume control approach, or are the perceptual differences negligible?
Hence, we conducted a spatial realism experiment to evaluate these two methods. Healthy volunteers were recruited for an anonymous online study. Participants were asked to listen to audio samples

representing five distinct sound sources (a car, a crying baby, footsteps, a singing child, and a dog barking). Each sample was presented in three formats: (1) static stereo (no movement), (2) dynamic volume control simulating movement at 10°/s, and (3) HRTF-based audio simulating movement at 10°/s. To minimize bias, participants were not informed which method was used for any given sample. Each participant evaluated all 15 audio files, rating how realistic the illusion of the sound moving from right to left was on a 0–100 scale (0 = completely unrealistic, 100 = highly realistic). These realism ratings were provided via an online questionnaire interface. The hypothesis for this experiment was that the movement in the HRTF audio condition would be judged as more realistic than in the dynamic volume control audio condition, and that both HRTF and dynamic volume control would be significantly more realistic than stereo without movement.

Selecting Engaging Audio Content

To maximize patient motivation and adherence, the selection of the audio content is a relevant factor. Two possible contents of the audio signal have been considered: 1) *Realistic Soundscapes:* These include everyday auditory experiences such as footsteps moving from right to left or a car driving past. Such sounds align with real-world expectations, making them highly effective in evoking spatial perception. Studies in ecological acoustics [20] suggest that familiarity with natural sounds enhances spatial awareness and immersion. 2) *Entertaining Content:* This category includes musical compositions, entertainment programs, and informational broadcasts. While not inherently directional, these sounds can be spatialized to create the illusion of a sound source travelling from the right to the left side. Research on immersive audio [21] indicates that even abstract audio elements, when processed through spatial techniques, can evoke a sense of movement.
Both approaches offer valuable contributions to the Neglect Radio concept. Realistic sounds provide strong spatial cues grounded in everyday experiences, while entertaining content potentially enhances engagement and listener retention. Based on previous experiences Kaufmann et al. (2022) [13], we assume that repeatedly listening to realistic soundscapes alone—despite their significant spatial effect—can become somewhat monotonous over extended time periods. Therefore, we suspect that an effective everyday audio stimulation should contain entertaining content such as radio programs.

Radio listening habits among individuals over the age of 65 are influenced by various factors, including environment, personal preference, and accessibility. Studies have shown that seniors tend to consume audio content in different ways depending on whether they are at home or in the car [22]. Older adults frequently listen to radio programs, especially in the morning and evening hours. Radio remains a popular medium due to its ease of use and familiar format. According to the ARD/ZDF-Media Commission [23], 78% of individuals over 30 years old listen to the radio at least once per week, and among individuals over 60 years old, the average daily listening time on Saturdays is approximately 200 minutes. This highlights the radio's role as a significant source of information and entertainment, particularly at home, where it is often used as background audio during daily activities.

Many individuals over 65 continue to cherish personal music collections, often consisting of CDs or digital playlists featuring music that reflect the soundtrack of their youth. Research by Hays and Minichiello (2005) [24] suggests that listening to familiar music enhances cognitive function and emotional well-being in older adults. Studies also indicate that about 20% of daily audio listening in the U.S. consists of personal music collections, including CDs and digital files. While these findings may not directly translate to all regions of the world, they suggest a continued preference for personal music among older adults. For practical and legal reasons, the application focuses on streaming publicly available web radio programs rather than personal music files, ensuring a wide variety of content without copyright barriers.

Implementing the neglect radio smartphone app

Based on chapters 2.1 and 2.2 as well as previous experiments [13-15], the neglect radio smartphone application was designed to fulfil the following functional requirements:

1. Playback of web radio stations: The app streams internet radio broadcasts to provide continuous audio content.
2. Adjustable movement speed: The angular velocity of the virtual sound source can be adjusted from 5°/s to 40°/s (default 10°/s). This range was chosen based on pilot testing to ensure the motion is perceivable yet comfortable for listeners.
3. Integration of spatial audio via HRTFs: Audio output is rendered with head-related transfer functions to simulate a moving sound source in 3D space.
4. Multilingual support: Both the app interface and available radio content are offered in multiple languages (initially German, French, and English) to cater to diverse user groups.
5. Region-based content selection: The application selects radio stations based on the user's language region, ensuring culturally relevant and familiar content (e.g., French stations for French-speaking users).
6. Multi-platform availability: The app supports multiple platforms and is distributed via standard app stores for both iOS (Apple) and Android devices.

Based on the functional requirement 6, it was decided to use the Unity3D (6.1) programming environment for application development, allowing to deploy the frontend application to both Android and Apple smartphones. Also, Unity3D provides a spatial audio function using the HRTF method. PhP (8.3) and SQL are used for the backend with user management function and daily usage duration storage.

To assess the usability of the app, participants of the spatial hearing evaluation (chapter 2.1) were invited to test a prototype of the app. The testing procedure involved 15-minute radio hearings through the app, followed by completion of an online version of the system usability scale [25] originally developed by Brooke et al. (1996) [26] for usability testing.

Results

Spatial Realism Experiment

A total of 37 volunteers participated in the online study, listening to five audio sources in three different conditions each (HRTF, non-moving stereo and volume control) and rating them with respect to the "impression that the sound source moves from the right to the left." The evaluation was conducted on a scale from 0 to 100, with 0 indicating a very unrealistic and 100 a very realistic impression. The detailed descriptive statistics for each condition are presented in the table (Table 1). (Figure 1) illustrates the distribution of realism ratings across the three audio conditions.

Table 1. Results from the Realism Rating experiment with the three conditions (HRTF, non-moving stereo and volume control).

		Realism Rating	
	HRTF	Non-moving Stereo	Volume Control

Valid	37	37	37
Missing	0	0	0
Mean	80.903	15.195	65.141
Std. Deviation	21.237	16.404	14.585
Shapiro-Wilk	0.833	0.823	0.976
P-Value of Shapiro-Wilk	<.001	<.001	0.599
Minimum	12.600	1.000	35.800
Maximum	100.000	53.800	100.000

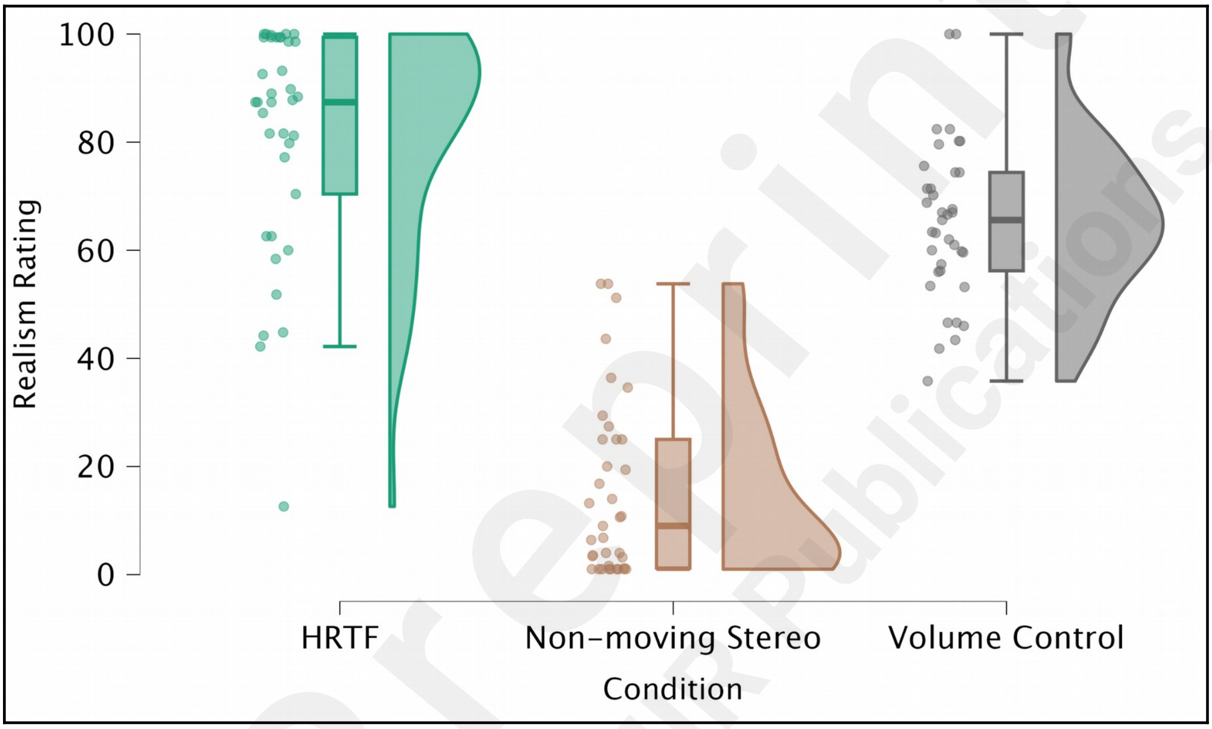

Figure 1: Realism Rating for the three conditions. HRTF stands for Head-related-transfer-function.

The realism rating for the HRTF is significantly greater than for the volume control (Independent samples T-Test, t = 3.722, df, p<0.001), and the non-moving stereo condition is significantly smaller than the other two groups.

Usability Evaluation

The developed Neglect Radio smartphone application was created using the Unity game engine and is available on the Apple Store. (Figure 2) shows the main user interface of the Neglect Radio application. The source code for the frontend (Unity3D) and the backend (SQL, PHP) is published on GitHub under an open-source license.

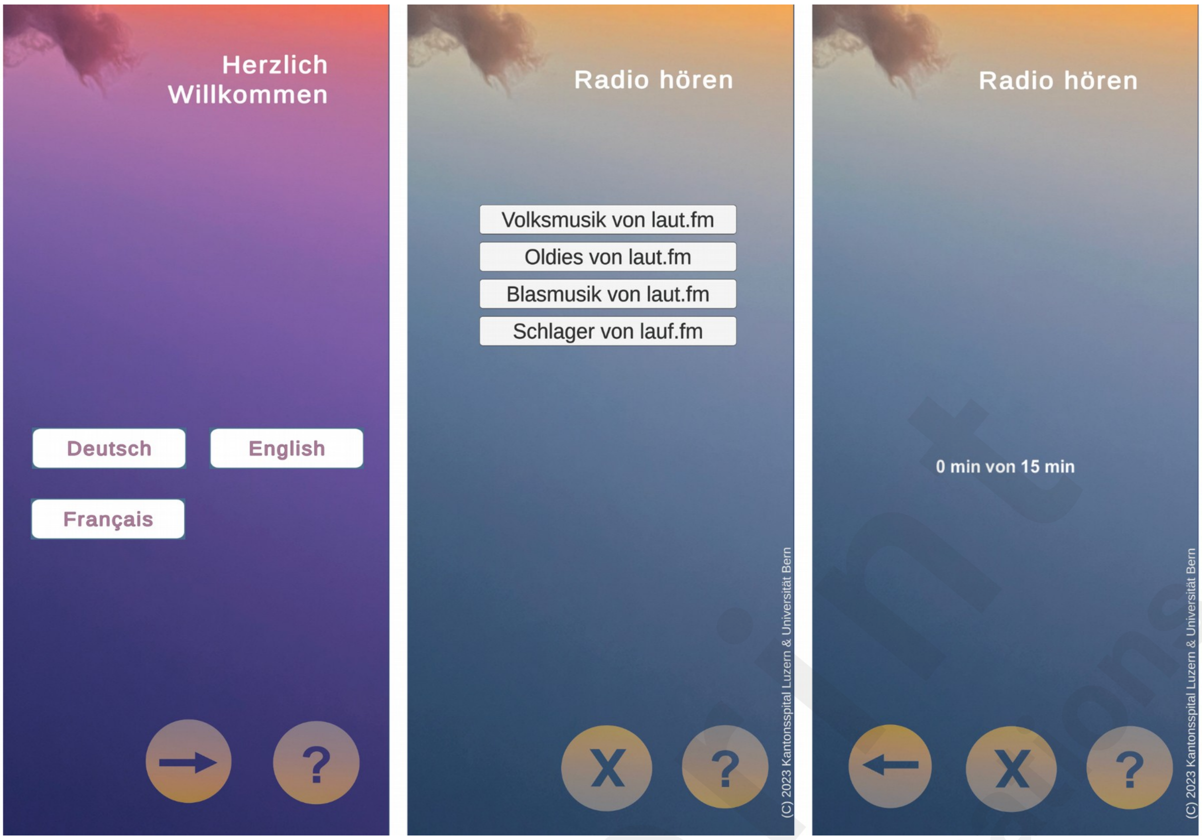

Figure 2: Screenshots of the smartphone app. Participants can select the language (German, English, or French). They can then select a radio station from the laut.fm screening service and listen to the spatial presentation of the audio. While listening, the total listening time in minutes is shown on screen.

Ten participants tested the Neglect Radio application prototype for 15 minutes each and filled out the System Usability Scale questionnaire. The individual System Usability Scale scores are shown in (Figure 3).

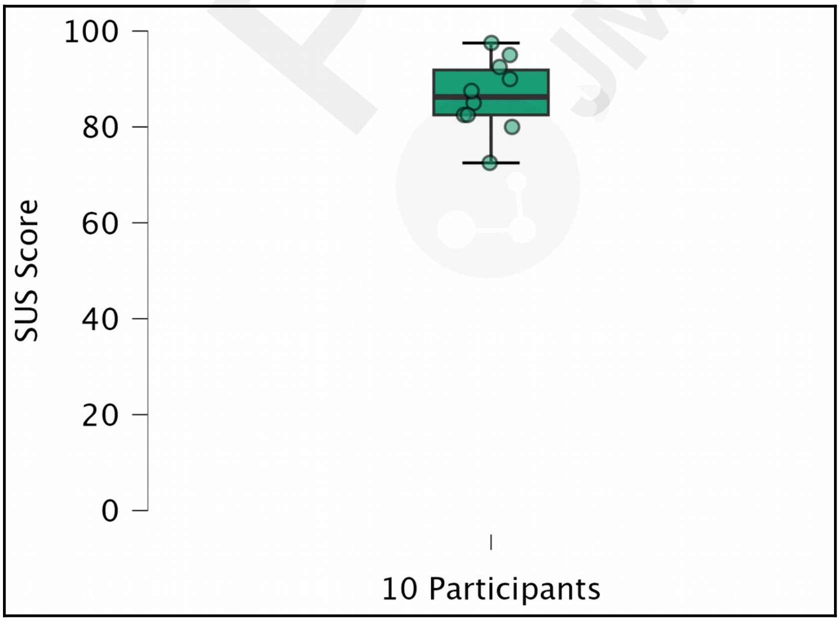

Figure 3: System Usability Scale responses from 10 participants. A total score of more than 68 is

considered as above average [27]. Following the interpretation of Bangor et al. (2009) [28], the mean score of 86.5 may be described as excellent.

Discussion and Conclusion

The present study introduced Neglect Radio, a smartphone-based spatial audio application, and evaluated the realism of its sound and its usability. Participants rated the head-related transfer function (HRTF) spatial audio as more realistic than both the simple volume-control and the static stereo versions. In fact, HRTF-based 3D audio cues were perceived as significantly more natural in simulating a sound moving from right to left, compared to volume-controlled or non-moving stereo playback. This finding suggests that leveraging HRTFs can create a compelling illusion of sound motion, likely because it reproduces the subtle timing and filtering cues that the brain expects from real-world sound sources [17,18]. In a rehabilitation context, higher perceptual realism may be important, since realistic spatial cues could engage patients' attention more effectively and promote a stronger sense of motion [28]. The application also received an excellent usability rating, with a mean SUS score of 86.5, corresponding to superior usability [29]. This indicates that users – even those unfamiliar with advanced technology – found the application intuitive, comfortable, and engaging to use. Such positive reception is encouraging, as it meets a relevant requirement for rehabilitation tools: If an intervention is not user-friendly, patients (especially elderly stroke survivors) are unlikely to adopt it in their daily [15]. Taken together, these results validate the core design choices of Neglect Radio: using HRTF-based spatial sound to maximize realism and delivering the intervention via a smartphone application that patients can easily operate.

The clinical potential of the Neglect Radio lies in its accessibility and scalability, providing auditory stimulation to patients irrespective of their location, even allowing home-based use. Its intuitive interface makes it suitable for elderly users, aligning with real-world usability needs. Integrating this technology into existing rehabilitation protocols could enhance therapeutic outcomes by offering continuous attention training, from the inpatient to the home-based setting. Furthermore, the passive logging of application usage provides clinicians with valuable adherence data, enabling them to deliver personalized care.

This study has also some limitations, including a small sample size for usability testing, the use of healthy participants rather than neglect patients, a short exposure duration, and the absence of direct clinical efficacy measures. These aspects call for caution regarding the generalisability of the findings and highlight the importance of subsequent patient-focused evaluations. These limitations are partially addressed by the work by Geiser et al. 2024 and 2025 using an early prototype for clinical evaluation, confirming similar feasibility results in stroke patients [15, 14].

Future research should focus on clinical validation through controlled trials involving neglect patients and assessing long-term adherence, patient engagement, and functional outcomes. Additionally, refinement of content personalization, integration of multimodal stimuli (e.g., augmented reality or vibrotactile cues), and enhanced application customization could further optimize patient outcomes. Longitudinal studies are also needed to assess sustained user engagement and therapeutic benefits.

In conclusion, Neglect Radio demonstrates promising realism, usability, and potential therapeutic benefits as a home-based rehabilitation tool for hemispatial neglect. By effectively leveraging spatial auditory stimulation through an engaging smartphone interface, it addresses critical barriers in neglect rehabilitation, offering a scalable, accessible, and patient-friendly intervention. Further clinical validation and refinement are essential next steps to firmly establish its role in clinical practice.

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Conflicts of Interest

None declared.

Abbreviations

JMIR: Journal of Medical Internet Research
HRTF: Head-Related Transfer Function
SUS: System Usability Scale
PhP: PHP (Hypertext Preprocessor)
SQL: Structured Query Language
RCT: Randomized Controlled Trial

References

1. Kerkhoff G, Rode G, Clarke S. Treating Neurovisual Deficits and Spatial Neglect. *Clinical Pathways in Stroke Rehabilitation*. Published online 2021:191-217. doi:https://doi.org/10.1007/978-3-030-58505-1_11
2. Corbetta M, Shulman GL. Spatial Neglect and Attention Networks. *Annual Review of Neuroscience*. 2011;34(1):569-599. doi:https://doi.org/10.1146/annurev-neuro-061010-113731
3. Cazzoli D, Kaufmann BC, Henrik Rühe, Geiser N, Nyffeler T. Incidence of Visuospatial Neglect in Acute Stroke: Assessment and Stroke Characteristics in an Unselected 1-Year Cohort. *Stroke*. Published online April 7, 2025. doi:https://doi.org/10.1161/strokeaha.124.048907
4. Klinke ME, Hafsteinsdóttir TB, Hjaltason H, Jónsdóttir H. Ward-based interventions for patients with hemispatial neglect in stroke rehabilitation: A systematic literature review. *International Journal of Nursing Studies*. 2015;52(8):1375-1403. doi:https://doi.org/10.1016/j.ijnurstu.2015.04.004
5. Spence C, Driver J. Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*. 1996;22(4):1005-1030. doi:https://doi.org/10.1037//0096-1523.22.4.1005
6. Bavelier D, Neville HJ. Cross-modal plasticity: where and how? *Nature Reviews Neuroscience*. 2002;3(6):443-452. doi:https://doi.org/10.1038/nrn848

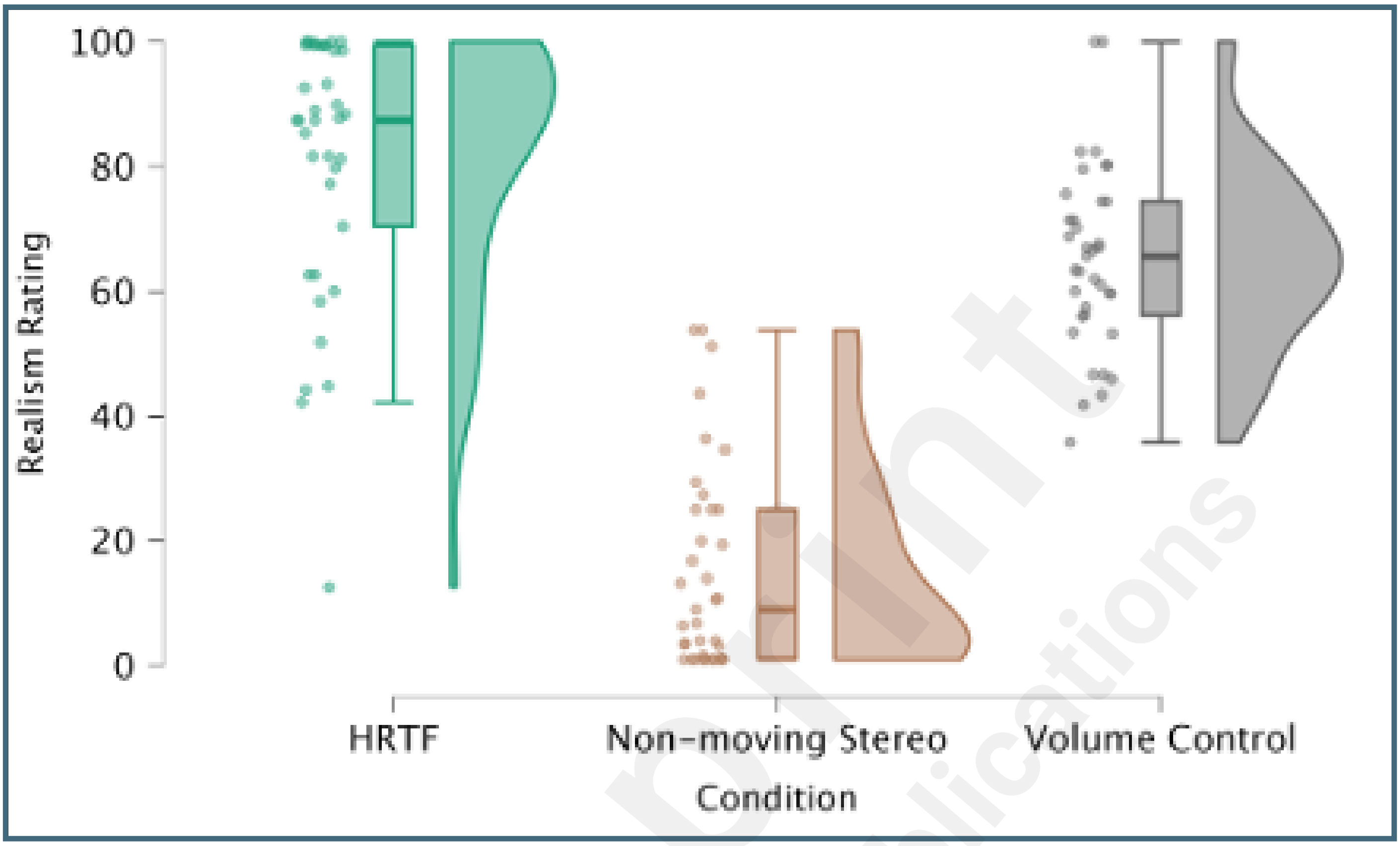
7. Bolognini N, Convento S, Casati C, Mancini F, Brighina F, Vallar G. Multisensory integration in hemianopia and unilateral spatial neglect: Evidence from the sound induced flash illusion. *Neuropsychologia*. 2016;87:134-143. doi:https://doi.org/10.1016/j.neuropsychologia.2016.05.015
8. Zigiotto L, Damora A, Albini F, et al. Multisensory stimulation for the rehabilitation of unilateral spatial neglect. *Neuropsychological Rehabilitation*. Published online June 19, 2020:1-34. doi:https://doi.org/10.1080/09602011.2020.1779754
9. Lewald J, Tegenthoff M, Peters S, Hausmann M. Passive Auditory Stimulation Improves Vision in Hemianopia. Greenlee MW, ed. *PLoS ONE*. 2012;7(5):e31603. doi:https://doi.org/10.1371/journal.pone.0031603
10. Chen MC, Tsai PL, Huang YT, Lin K. Pleasant music improves visual attention in patients with unilateral neglect after stroke. *Brain Injury*. 2012;27(1):75-82. doi:https://doi.org/10.3109/02699052.2012.722255
11. Soto D, Funes MJ, Guzmán-García A, Warbrick T, Rotshtein P, Humphreys GW. Pleasant music overcomes the loss of awareness in patients with visual neglect. *Proceedings of the National Academy of Sciences*. 2009;106(14):6011-6016. doi:https://doi.org/10.1073/pnas.0811681106
12. Long J, Zhang Y, Liu X, Gao Q, Pan M. Music-based interventions for unilateral spatial neglect: A systematic review. *Neuropsychological Rehabilitation*. Published online August 18, 2022:1-26. doi:https://doi.org/10.1080/09602011.2022.2111314
13. Kaufmann BC, Cazzoli D, Bartolomeo P, et al. Auditory spatial cueing reduces neglect after right-hemispheric stroke: A proof of concept study. *Cortex*. 2022;148:152-167. doi:https://doi.org/10.1016/j.cortex.2021.12.009
14. Geiser N, Kaufmann BC, Cazzoli D, Nef T, Nyffeler T. Auditory motion stimulation as an add-on therapeutical approach is feasible, enjoyable, and associated with a significant improvement of neglect outcome: A non-randomized, controlled group-matched study. *Neuropsychological Rehabilitation*. Published online March 14, 2025:1-15. doi:https://doi.org/10.1080/09602011.2025.2476068
15. Geiser N, Kaufmann BC, Knobel S, Cazzoli D, Nef T, Nyffeler T. Comparison of uni- and multimodal motion stimulation on visual neglect: a proof-of-concept study. *Cortex*. 2024;171:194-203. doi:https://doi.org/10.1016/j.cortex.2023.10.018
16. Blauert J. *Spatial Hearing : The Psychophysics of Human Sound Localization*. The Mit Press; 1997. ISBN: 9780262024136
17. Hartmann, W. M. (1999). How we localize sound. Physics Today, 52(11), 24-9. ISSN: 0031-9228
18. Wightman FL, Kistler DJ. Headphone simulation of free-field listening. II: Psychophysical validation. *The Journal of the Acoustical Society of America*. 1989;85(2):868-878. doi:https://doi.org/10.1121/1.397558
19. Begault DR. *3-D Sound for Virtual Reality and Multimedia*. Ap Professional; 1994. No. NASA/TM-2000-209606. 2000.
20. Gaver WW. How Do We Hear in the World? Explorations in Ecological Acoustics. *Ecological Psychology*. 1993;5(4):285-313. doi:https://doi.org/10.1207/s15326969eco0504_2
21. Zahorik P, Wightman FL. Loudness constancy with varying sound source distance. *Nature Neuroscience*. 2001;4(1):78-83. doi:https://doi.org/10.1038/82931
22. Cherubini F, Nielsen RK. Editorial Analytics: How News Media are Developing and Using Audience Data and Metrics. *SSRN Electronic Journal*. Published online 2016. doi:https://doi.org/10.2139/ssrn.2739328
23. ARD MEDIA GmbH. Die ARD MEDIA GmbH vermarktet die Werbung in der ARD und ermöglicht die Schaltung von Werbespots in TV und Radio und im privaten Rundfunk. Ard-media.de. Published 2025. Accessed August 13, 2025. https://ard-media.de

24. Hays T, Minichiello V. The meaning of music in the lives of older people: a qualitative study. *Psychology of Music*. 2005;33(4):437-451. doi:https://doi.org/10.1177/0305735605056160
25. System Usability Scale (SUS) Score Calculator. stuart-cunningham.github.io. https://stuart-cunningham.github.io/sus/ Accessed August 13, 2025.
26. Jordan PW, Thomas B, Ian Lyall Mcclelland, Weerdmeester B. *Usability Evaluation in Industry*. Boca Raton Chapman And Hall/Crc; 2014.
27. Sauro J, Lewis J. *Quantifying the User Experience : Practical Statistics for User Research*. Morgan Kaufmann; 2016. ISBN:978-0-12-802308-2
28. Pedroli E, Serino S, Cipresso P, Pallavicini F, Riva G. Assessment and rehabilitation of neglect using virtual reality: a systematic review. *Frontiers in Behavioral Neuroscience*. 2015;9. doi:https://doi.org/10.3389/fnbeh.2015.00226
29. BangorAaron, KortumPhilip, MillerJames. Determining what individual SUS scores mean. *Journal of Usability Studies archive*. Published online May 1, 2009. doi:https://doi.org/10.5555/2835587.2835589

Supplementary Files

Figures

Realism Rating for the three conditions. HRTF stands for Head-Related Transfer Function.



Screenshots of the smartphone app. Participants can select the language (German, English, or French). They can then select a radio station from the laut.fm screening service and listen to the spatial presentation of the audio. While listening, the total listening time in minutes is shown on screen.

System Usability Scale responses from 10 participants. A total score of more than 68 is considered as above average [27]. Following the interpretation of Bangor et al. (2009) [28], the mean score of 86.5 may be described as excellent.