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Systematic Review and Meta-Analysis of the Application of Virtual Reality in Hearing Disorders

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Background and Objectives: Trendy technologies, such as artificial intelligence, virtual reality (VR), and augmented reality (AR) are being increasingly used for hearing loss, tinnitus, and vestibular disease. Thus, we conducted this systematic review and meta-analysis to identify the possible benefits of the use of VR and AR technologies in patients with hearing loss, tinnitus, and/or vestibular dysfunction, with the aim of suggesting potential applications of these technologies for both researchers and clinicians. **Materials and Methods**: Published articles from 1968 to 2022 were gathered from six electronic journal databases. Applying our specified inclusion and/or exclusion criteria, 23 studies were analyzed. As only one article on hearing loss and two articles on tinnitus were found, 20 studies on vestibular dysfunction were only finally included for the meta-analysis. Standardized mean differences (SMDs) were chosen as estimates to compare the studies. A funnel plot and Egger's regression analysis were used to identify any risk of bias. **Results**: High heterogeneity (I^2: 83%, τ^2: 0.5431, $p<0.01$) was identified across the studies on vestibular dysfunction. VR-based rehabilitation was significantly effective for individuals with vestibular disease (SMDs: 0.03, 95% confidence interval [CI]: -0.08 to 0.15, $p<0.05$). A subgroup analysis revealed that only improvement in the subjective questionnaire was meaningful and statistically significant (SMDs: -0.66, 95% CI: -1.10 to -0.22). **Conclusions**: VR-based vestibular rehabilitation showed potential for subjective rating measures like Dizziness Handicap Index. The negative effect of aging on vestibular disease was indirectly confirmed. More clinical trials and an evidence-based approach are needed to confirm the implementation of state-of-the-art technology for hearing loss and tinnitus, representative diseases in neurotology. **J Audiol Otol 2022;26(4):169-181**

Keywords: Hearing loss; Vestibular disease; Tinnitus; Virtual simulation; Digital treatment.

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Introduction

Recently, advanced technologies such as artificial intelligence (AI) and virtual reality (VR) make our lifestyles more convenient and were even boosted by the COVID-19 pandemic by having the advantage of non-face-to-face interactions [1,2]. AI is defined as computer algorithms with the ability to automate cognitive processes [3]. Its concept is extensively smeared in our daily life. That is, no more surprising than the advertisement which we liked on my Google help search specific results. Also, many people are helped by personal assistants [4] like Siri and/or Alexa in iPhone and Bixby in the Galaxy smartphone. These AI techniques consist of various sub-technologies that make it possible to identify the patterns in the big data like providing a graphic-analyzing algorithm for medical imaging analysis [3]. On the other hand, a more sensory-focused simulation technology called VR is also highlighted. VR is defined as an immersed real-time simulation of the user in an interactive environment that mimics reality [5,6]. It has commercialized different games and sports that the whole family can enjoy together by connecting it to a home TV.

Interestingly, these advanced technologies have also influenced the medical fields, especially for otology and/or audiology. For instance, the hearing aid can adjust gain automatically by utilizing machine learning, which is one of the AI subtypes [3,7,8]. The function of volume control and gain initially matched the preferred level of hearing aid users. The machine learning algorithm that is built into hearing aid software provides optimized sound levels in different sound environments. The notion of VR (i.e., sensory interaction including vision, hearing, smell, and touch) is like posturography which performs tridimensional sensory interaction between the visual, vestibular, and somatosensory systems. This method has been usually utilized for VR simulation by using goggles, e.g., the Samsung Gear and Google Cardboard platform [9-11] or the commercially available Computerized Dynamic Posturography device [12] or a video game console, such as Wii® and PlayStation [13]. In addition to these applications, the VR-based technique has been applied for use in tinnitus therapy [1,14], temporal bone surgery [15], and mastoidectomies [16,17].

Regardless, the clinical practice has not yet rapidly adapted to these technological changes. The technologies are being applied only to certain diseases in hearing loss, tinnitus, and vestibular disease. Although some studies have reported the efficacy and/or effectiveness of recent technologies especially for VR in otology by using the systematic review [18-20] and meta-analysis [3,6], most have been either inconclusive or lack enough topic diversity and/or subjective evidence and do not report any statistical significance. By using a systematic review and a meta-analysis approach, we sought to identify the VR technology applied to hearing loss, vestibular dysfunction, and tinnitus, indeed the representative diseases in the fields of otology and audiology. The goal was to analyze its applicability for hearing loss, tinnitus, and vestibular disease and suggest the scope of its potential application for both researchers and clinicians.

Materials and Methods

Search strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [21] and the International Prospective Register of Systematic Reviews (PROSPERO) of Cochrane Collaboration were adjusted to the methodological approach that contained inclusion criteria, an article search strategy, and article selection in the current systematic review and mete-analysis. The protocol of the present study was adopted from a similar methodological approach that is registered in the PROSPERO CRD42011001406.

The specific criteria, a strategy for Participants, Intervention, Control, Outcome measures, and Study design (PICOS), were used for setting up the inclusion criteria. Table 1 displays the PICOS criteria used in this study. Animal studies, general articles (e.g., conference abstracts, proceeding papers, books, and book chapters, and systematic and/or narrative reviews), and articles not written in English were excluded.

Article selection

Six electronic journal databases, Embase, MEDLINE, PubMed, Web of Science, Science Direct, and Cumulative Index to Nursing and Allied Health, were used to search for the articles. Timeframe for the article search and selection was set for January 1968 to February 2022 when articles that initially reported the technology called virtual reality head mounted display [22]. The key terms were 'hearing loss' OR 'dizziness' OR 'vertigo' OR 'vestibular disease' OR 'tinnitus' AND 'training' OR 'treatment' OR 'rehabilitation' AND 'virtual reality' OR 'augmented reality' OR 'metaverse' OR 'virtual simulation.' These terms were combined to minimize the need to filter out any duplicate papers.

The overall flow of systematic methodology used in the article selection is displayed in Fig. 1. In detail, a total of 16,511 records were searched by using six electronic journal databases. After eliminating 6,350 duplicates, 10,161 records remained. The titles and abstracts of 10,161 records were then screened, resulting in the exclusion of 9,079 records. The full texts of the

Table 1. Inclusion criteria for the current study based on Participants, Intervention, Control, Outcomes, and Study Designs (PICOS)

PICOS	Content
Participants	Individuals with hearing loss or vestibular disease or tinnitus
Intervention	Any training, therapy, treatment, and rehabilitation related to hearing ability or vestibular function or tinnitus symptom using virtual reality and/or augmented reality
Control	Comparison with a control group or repeated measures (experiments with additional purpose)
Outcomes	Outcome measure(s) related to audiological, vestibular, and tinnitus testing result(s)
Study design	Randomized controlled trials, non-randomized controlled trials, cohort studies (with a control comparison), and repeated measures (pre- and post-comparisons)

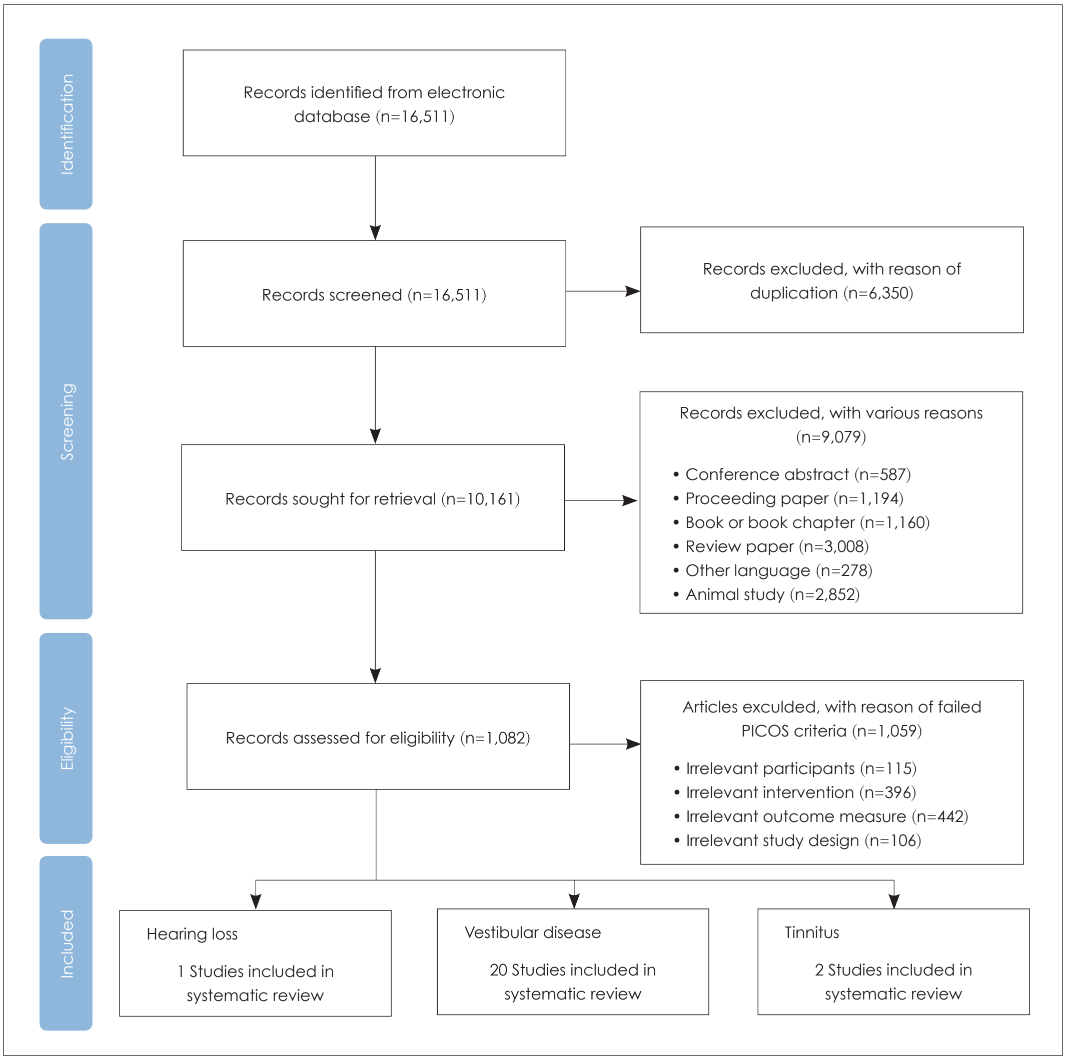

Fig. 1. Flowchart based on a Preferred Reporting Items for a Systematic Review and Meta-analysis (PRISMA) statement. PICOS, Participants, Intervention, Control, Outcome measures, and Study design.

remaining 1,082 records were then reviewed at the eligibility stage. Finally, only 23 records met the PICOS criteria for this study (Table 1), and they were included in the systematic review and meta-analysis. Throughout all the steps, any disagreement was resolved by consultation with the authors.

Study quality and potential sources of study bias

To evaluate both the study quality and any potential sources of study bias, we used the CAMARADES checklist [23]. This scale assesses the randomization, presence of controls, calculation of sample size, publication after peer review, outcome measures, and statement of potential conflicts of interest (Table 2). Each item was assigned 1 for "yes" or 0 for "no." The findings of the highest-scoring studies were the most valid.

The data contained in the articles were independently extracted and synthesized into six categories by the authors as 1) participants; 2) intervention; 3) control group; 4) study design; 5) outcome measures; and 6) main findings (Table 3).

Meta-analysis

The R Software (Ver. 4.2.0, R Core Team, R Foundation for Statistical Computing, Vienna, Austria) was used for the meta-analysis. Twenty articles related to vestibular disease were examined for their data synthesis process, especially in terms of their descriptive statistics (mean and standard deviation values in the experimental and control groups). After conducting the data synthesizing, a total of 12 articles were included in the meta-analysis. Standardized mean differences (SMDs) calculated the effect size for the individual study. Then, a summary estimate was examined. The random-effect model was selected to calculate both the effect size and summary estimate. The funnel plot and Egger's regression test were used to identify any

Table 2. Analysis using the scientific study validity criteria based on CAMARADES checklists

Study	1	2	3	4	5	6	Study quality score (point)
Wolter, et al. [25]	1	1	0	1	1	1	5
Cesaroni, et al. [12]	1	1	0	1	1	1	5
Cusin, et al. [26]	0	1	0	1	1	0	3
Garcia, et al. [27]	1	0	0	1	1	0	3
Gazzola, et al. [10]	1	1	0	1	1	1	5
Kanyılmaz, et al. [11]	1	1	0	1	1	1	5
Kasse, et al. [28]	0	0	0	1	1	0	2
Lança, et al. [29]	0	0	0	1	1	0	2
Mecedo, et al. [30]	1	0	0	1	1	1	4
Meldrum, et al. [31]	1	1	1	1	1	0	5
Micarelli, et al. [32]	1	1	0	1	1	1	5
Monteiro, et al. [33]	1	1	0	1	1	0	4
Pavlou, et al. [34]	1	1	0	1	1	0	4
Rosiak, et al. [35]	1	1	0	1	1	0	4
Stankiewicz, et al. [9]	1	1	0	1	1	0	4
Ugur, et al. [13]	0	1	0	1	1	1	4
Verdecchia, et al. [36]	0	0	0	1	1	1	3
Villard, et al. [37]	0	0	0	1	1	0	2
Viziano, et al. [38]	1	1	0	1	1	1	5
Whitney, et al. [39]	1	0	0	1	1	0	3
Yeh, et al. [40]	1	1	0	1	1	0	4
Bertet, et al. [41]	1	0	0	1	1	0	3
Malinvaud, et al. [14]	1	0	1	1	1	1	5

1 and 0 stand for "Yes" and "No," respectively. The CAMARADES checklist consisted of 6 items as follows: 1, randomization; 2, controls; 3, sample size calculation; 4, publication after peer review; 5, outcome measure; 6, statement of potential conflict of interest.

publication bias.

As the confirmation of heterogeneity, the Higgins I^2-statistics and Cochran's Q-test were applied. For the Higgins I^2-statistics, the value of I^2 was indicated as the percentage of heterogeneity. For example, the interval ranges from 0 to 25%, 25% to 75%, and 75% to 100% of I^2 value were implied as having low, middle, and high heterogeneity, respectively [24]. The Q values for the Cochran test indicated the total variance across the dataset of the articles. This test showed a statistical significance at 95% of confidence interval (CI), and heterogeneity across the dataset of articles. The articles were also categorized based on outcome measures, and a subgroup analysis was conducted to compare the area and rate of the Computerized Dynamic Posturography test, the power spectra with low frequency (LF_PS), and a Dizziness Handicap Index (DHI) questionnaire. Using a careful interpretation of the results of meta-analysis, all descriptive values of the meta-analysis in the current study had reversed meaning, which was negative and/or a minus value of outcome measure means a better outcome or being benefited by the intervention and vice versa.

Results

Evaluation of study quality

The study quality evaluated by the CAMARADES checklist showed a mean score of 6.64 (SD: 1.15, range: 4−8). To identify the difference in study quality between studies, a chi-square test was conducted. There were no significant differences between the quality of the studies (χ^2=5.8427, df=22, p=0.9998). Table 3 provided characteristics and main findings for all enrolled studies for the participants, the intervention, control group and the outcome of each study [9-14, 25-41].

Overall results of the meta-analysis

Again, the studies related to vestibular disease were included and analyzed using a meta-analysis because of the lack of sample studies in the other fields (i.e., hearing loss and tinnitus). Overall effect size was estimated with the random effect model (Supplementary Fig. 1 in the online-only Data Supplement). The overall estimates showed SMDs of 0.03 (95% CI: -0.08 to 0.15). The heterogeneity related values, like the Higgins I^2 and Cochran's Q estimates (expressed as τ^2) demonstrated that there was a high heterogeneity (83% of I^2 and 0.5431

Table 3. Characteristics and main findings for all enrolled studies for the participants, the intervention, control group, and the outcome of each study

Study	Participants	Intervention	Control group	Study design	Outcome measures	Main findings
Wolter, et al. [25]	18 Children (mean aged: 14.28, SD: 3.00) with SNHL-BVL who received bilateral CIs in sequential surgery	Virtual reality simulator, StreetLab, was used for balance testing.	36 Children (mean aged: 13.54, SD: 3.80) with normal hearing and vestibular function	Between-group comparison with repeated measures	Both static and dynamic balance function was measured using balance subtest of Bruininks-Oseretsky Test of Motor proficiency-2 (BOT-2)	There was small, but significant difference between CI on and off condition (estimate: 0.56, SD: 0.28, [F(1,85)=4.08, p=0.047, Cohen's f=0.22]). Moreover, there was also a small, but significant effect on the duration of implant (estimate: 0.49, SD: 0.19, [F(1,85)=6.64, p=0.02, Cohen's f=0.28]).
Cesaroni, et al. [12]	26 Patients with vestibular migraine (mean aged: 41.15, SD: 15.14)	Body balance evaluation through the posturography module integrated to visual stimuli, projected in BRU™ virtual reality goggles.	30 Adults (mean aged: 38.53, SD: 16.37) paired for age and gender with experimental group	Descriptive and analytical cross-sectional study	Sway velocity values (cm/s) and pressure center displacement area (cm^2)	The mean values of both the pressure center displacement area (cm^2) and sway velocity (cm/s) in the experimental group were higher than those of the control group in the 10 assessed conditions. These differences were statistically significant ($p<0.05$).
Cusin, et al. [26]	30 Patients with Menière's disease (mean aged: 45.67, SD: 13.01)	BRU™ 17 posturography was carried out in a silent and dim room of about six square meters. The equipment included a computer with the evaluation software, safety metal structure, protection support system with harnesses and a safety belt, a force platform, virtual reality goggles, accelerometer and a foam pillow.	40 Healthy adults (mean aged: 45.55, SD: 12.36) matched with age and gender	Between-group comparison with repeated measures	Oscillatory velocity (cm/s) and elliptical area (cm^2) of the BRU™	There were no statistically significant differences (p=0.635) between the values of the stability limit area (cm^2) of the control group (mean=184.60; SD=48.46; median=188.50; variation=91−277) and the values from the group with Ménière's disease (mean =181.43; SD=59.76; median=174.00; variation=70−292).
Garcia, et al. [27]	23 Patients (mean aged: 47.65, age from 20 to 60) with unilateral Ménière's disease (22 patients)	BRU™ was used to assess and rehabilitate patients with dizziness and associated symptoms by providing them with visual stimuli projected in virtual reality goggles.	21 Patients (mean aged: 47.65, age from 20 to 60) with unilateral Ménière's disease (21 patients)	Between-group comparison with repeated measures	DHI, dizziness analog scale, posturography test	For areas of COP test, case group subject COP areas in the firm surface with eyes closed, and compliant surface with eyes closed conditions were significantly smaller after the intervention. Also, case group subjects showed significantly lower oscillation rates in the compliant surface with eyes closed condition and significantly higher oscillation rates in conditions of saccade stimulation and optokinetic stimulation in the vertical direction.

Table 3. Characteristics and main findings for all enrolled studies for the participants, the intervention, control group, and the outcome of each study (continued)

Study	Participants	Intervention	Control group	Study design	Outcome measures	Main findings
Gazzola, et al. [10]	76 Patients were subdivided into two groups: G1, without a history of falls in the past 6 months (n=40); G2, with a history of falls within the same period (n=36)	A computerized posturography system integrated with a virtual reality system that measures postural sway resulting from different stimuli	41 Healthy adults	A cross-sectional study	LOS and 95% confidence intervals of COP, mean value of VOS	The values of COP area were significantly different between G1 and G2 in conditions 1−4, 6, 8, and 9. The VOS values were also significantly differed between G1 and G2 in conditions 1 and 2.
Kanyılmaz, et al. [11]	16 Patients who received supervised vestibular rehabilitation supported with virtual reality	Vestibular exercises were applied for three weeks, 5 times per week, 2 sets of 15 min, with a 5 min break between sets, for a total of 35 min in both groups.	16 Patients who received supervised vestibular rehabilitation supported without virtual reality	Prospective, randomized, single-blind, single-center, controlled study	VVS-SF questionnaire, clinical dynamic balance (i.e., BBT), postural stability test, functional mobility test (i.e., TUG), IFES questionnaire, GDS questionnaire, and HAS questionnaire	There were significantly greater improvements in the VSS, subgroups of DHI, BBT, HAS in group comparison at the time window of 6 months after treatment ($p<0.05$).
Kasse, et al. [28]	20 Elderly patients (age over 60 years) with BPPV (mean aged: 68.15, SD: 6.06)	The BRU™ posturography module provides information on the COP of the patient by means of quantitative indicators: stability limit area and elliptical area, in ten sensorial conflict situations.	N/A	A clinical prospective study	Epley's repositioning maneuver, Brandt-Daroff test, Dix-Hallpike test, BRU™ static posturography situations, and DHI questionnaire	Stability limit area showed a statistically significant difference (p=0.001) when compared to pre (139.05±59.96 cm^2) and post (181.85±45.76 cm^2) Epley's maneuver.
Lança, et al. [29]	23 Elderly patients with BPPV	The BRU™ static posturography mode with integrated with visual stimuli used to assess patients with balance disorders, vertigo or instability	N/A	A longitudinal, descriptive and analytical study	Balance related outcomes such as static limit (cm^2), pressure center shifting area (cm^2), and body sway velocity (cm/s)	There was a significant difference in body sway velocity results in the condition 1 (p=0.044), 2 (p=0.002), 3 (p=0.001), 4 (p=0.004), 9 ($p<0.001$), and 10 (p=0.008).

Table 3. Characteristics and main findings for all enrolled studies for the participants, the intervention, control group, and the outcome of each study (continued)

Study	Participants	Intervention	Control group	Study design	Outcome measures	Main findings
Mecedo, et al. [30]	123 Elderly patients with chronic vestibular dysfunction	The CTSIB and posturography integrated with virtual reality (BRU™) were used.	N/A	A descriptive, analytical, cross-sectional study	Test progression of CTSIB and COP area (cm^2)/VBS (cm/s) of BRU™	There were significant differences between means of COP area. A significant increase from conditions 1 to 2 (p=0.013), 3 to 4 vertical (p=0.001), 4 to 5 horizontal (p<0.001), 4 to 5 vertical (p<0.001), 5 horizontal to 6 (p<0.001), and 5 vertical to 6 (p<0.001) were observed.
Meldrum, et al. [31]	35 Unilateral peripheral vestibular loss patients with virtual reality based balance exercise	Virtual reality based balance exercises during vestibular rehabilitation	36 Unilateral peripheral vestibular loss patients with conventional balance exercise	Randomized controlled trial	Self-preferred gait speed, sensory organization test, dynamic visual acuity, and questionnaires such as Hospital Anxiety and Depression Scale, Vestibular Rehabilitation Benefits Questionnaire, and ABC Questionnaire	There were no significant differences between the methods of balance exercise (virtual reality versus conventional) groups in self preferred gait speed at 8 weeks (mean difference: -0.03 m/s, 95% confidence interval: -0.09 to 0.02, p=0.23).
Micarelli, et al. [32]	23 Right chronic unilateral vestibular hypofunction patients with vestibular rehabilitation and HMD protocol	Otoneurological testing (i.e., vHIT), static posturography testing, and self-reported questionnaires such as DHI, ABC, Zung Instrument for Anxiety Disorders, and DGI	24 Right chronic unilateral vestibular hypofunction patients with vestibular rehabilitation	Randomized controlled trial	Posturography parameters, spectral values, and VOR gain	Regarding the vHIT analysis of VOR gain in the lesional side, a significant (p=0.0031) post-treatment VOR gain improvement was found in HMD when compared with the vestibular rehabilitation group.
Monteiro, et al. [33]	45 Patients (mean aged 49.13 years, SD: 9.53) with BPPV	The BRU™ posturography	45 Age- and gender-matched healthy adults (mean aged: 45.62 years, SD: 11.84)	A longitudinal, descriptive and analytical study	Values of ellipse area, sway velocity in firm surface, and saccadic stimulation	There were no statistically significant differences (p=0.597) between the values of the stability limit area (cm^2) for the control group (mean=183.24, SD=49.94, median=190.00, variation=77−277) and those from the BPPV group (mean=189.53, SD=61.92, median=179.00, variation=35−338).

Table 3. Characteristics and main findings for all enrolled studies for the participants, the intervention, control group, and the outcome of each study (continued)

Study	Participants	Intervention	Control group	Study design	Outcome measures	Main findings
Pavlou, et al. [34]	5 Peripheral vestibular deficit patients with dynamic virtual reality vestibular exercise	Virtual reality-based vestibular exercise and home vestibular exercise program	11 Peripheral vestibular deficit patients with static virtual reality vestibular exercise	Between-group comparison with repeated measures	Subjective visual vertigo, psychological symptoms, and functional gait	A significant difference was noted between groups (U=4.0, z=-2.68, $p=0.01$) with a 59% improvement for the former compared to 7.2% for the latter.
Rosiak, et al. [35]	25 Peripheral vestibular dysfunction patients with hybrid virtual reality unit	Vestibular rehabilitation using virtual reality and conventional program	25 Peripheral vestibular dysfunction patients with static posturography with visual feedback	A prospective, non-randomized, controlled group study	Posturography parameters (i.e., length and surface) and subjective questionnaire	Comparing outcomes within the groups, both the length and square surface of the COP decreased in time; however, in the quiet stance with eyes open, there was no significant change in the COP surface median.
Stankiewicz, et al. [9]	10 Unilateral vestibular hypofunction patients with virtual reality-based vestibular rehabilitation	Vestibular rehabilitation using virtual reality and conventional program	10 Unilateral vestibular hypofunction patients with conventional therapy	Between-group comparison with repeated measures	VSS-SF and VAS questionnaire	Results in Group 1 at initial VSS-SF assessment were 13.70 (SD: 4.19) and final VSS-SF assessment (mean: 6.70, SD: 4.17). Results in Group 2 initial VSS-SF assessment were 15.10 (SD: 4.89) and final VSS-SF assessment (mean: 9.60, SD: 4.12).
Ugur, et al. [13]	19 Motion sickness patients with virtual reality rehabilitation	Rehabilitation using virtual reality and conventional test	20 Normal adults with conventional test	Between-group comparison with repeated measures	Equilibrium scores of SOT	The SOT-equilibrium scores of the 2nd conditions between patient and control groups did not show statistically significant difference for the 1st SOT ($p>0.05$).
Verdecchia, et al. [36]	69 Chronic unilateral vestibular hypofunction	Conventional vestibular rehabilitation using Nintendo Wii® video game	N/A	Retrospective chart review study	DGI, clinical DVA test, and DHI questionnaire	All patients were improved their DGI (21 to 23 points), DHI (40 to 24 points), DVA (2 to 1 points) results.
Villard, et al. [37]	5 Young adults age ranged 20 to 22 years assigned sick group	Oscillating virtual environment using video projector	7 Young adults age ranged 20 to 22 years assigned well group	Between-group comparison with repeated measures	SSQ, spontaneous sway such as head variability and velocity in mediolateral and anteroposterior view	For the well group, the pretest scores of SSQ (mean rank=10.3) did not differ from the posttest scores (mean rank=4.3), z=-2.02, $p>0.025$. For the sick group, posttest scores (mean rank=103.2) were significantly higher than pretest scores (mean rank=5.2), z=-2.26, $p<0.025$.

Table 3. Characteristics and main findings for all enrolled studies for the participants, the intervention, control group, and the outcome of each study (continued)

Study	Participants	Intervention	Control group	Study design	Outcome measures	Main findings
Viziano, et al. [38]	24 Unilateral vestibular hypofunction patients with head-mounted gaming home exercise	Vestibular rehabilitation program with head-mounted exercise	23 Unilateral vestibular hypofunction patients with conventional vestibular rehabilitation	Randomized controlled trial	VOR gain, classical posturography scores, and self-reported questionnaire such as DHI	No significant within-subjects differences in values measured one week and 12 months after treatment were found in either group.
Whitney, et al. [39]	2 Patients with unilateral vestibular loss	Virtual reality grocery store environment	3 Healthy adults	Between-group comparison with repeated measures	DGI questionnaire, SSQ questionnaire, distance traveled, and speed of head movement	Although subjects with vestibular dysfunction traveled as far as the controls, the older subjects did not moved as far as the young subjects.
Yeh, et al. [40]	48 Patients with chronic vestibular dysfunction	Interactive virtual reality game-based vestibular rehabilitation program	36 Healthy adults	Between-group comparison with repeated measures	Quantified balance indices including mediolateral and anteroposterior head movement and statokinesigram	There were significant differences between patients and healthy counterparts in overall balance indexes ($p<0.05$), except for mean mediolateral head movement ($p=0.147$) and statokinesigram ($p=0.062$).
Bertet, et al. [41]	22 Patients with tonal and stable unilateral tinnitus in different test session	Tinnitus avatar synthesis method	N/A	Repeated measures	Subjective questionnaires such as VAS and 7-point horizontal scale	A linear fit across the individual curves revealed that a range of 29 dB was required to obtain a full lateral shift from the ipsilateral to the contralateral side. It was also interesting to observe the negative intercept: -6.3 dB (±3.6 dB for 95 % confidence interval).
Malinvaud, et al. [14]	119 Patients which mixed groups such as virtual reality immersion group (n=61) and CBT group (n=58)	Mixed condition of virtual reality immersion in auditory and visual 3D environments and CBT	29 Patients with waiting list group	Randomized controlled trial	Tinnitus related indices (i.e., severity and handicap)	Three months after the end of the treatment, we did not find any difference between VR and CBT groups either for tinnitus severity ($p=0.99$) or tinnitus handicap ($p=0.36$).

SNHL-BVL, sensorineural hearing loss and bilateral vestibular loss; CI, cochlear implant; BRU™, balance rehabilitation unit; LOS, limit of stability; COP, center of pressure; VOS, velocity of oscillation; VSS, Vertigo Symptom Scale; BBT, Berg Balance Test; TUG, Timed-Up&Go; IFES, International Falls Efficacy Scale; GDS, Geriatric Depression Scale; HAS, Hamilton Anxiety Scale; N/A, not applicable; CTSIB, Clinical Test of Sensory Interaction and Balance; ABC, Activities Balance Confidence; VOR, vestibulo-ocular reflex; VBS, velocity of body sway; vHIT, video head impulse test; HMD, head-mounted display; VSS-SF, Vertigo Symptom Scale−short form; VAS, visual analog scale; SOT, sensory organization test; DGI, Dynamic Gait Index; DVA, dynamic visual acuity; SSQ, Simulator Sickness Questionnaire; CBT, cognitive behavior therapy

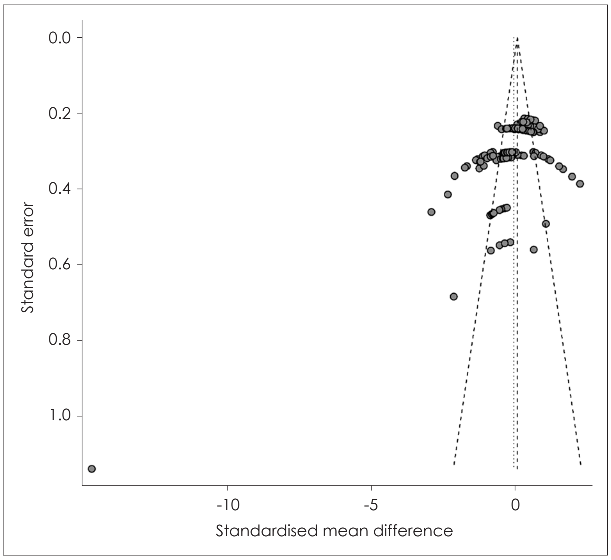

Fig. 2. Funnel plot for confirming publication bias.

of τ^2 with p<0.01). In Fig. 2, the funnel plot and Egger's regression analysis present that there was indeed significant publication bias (t=-7.76, df=183, p<0.0001).

Subgroup analysis

Based on the results of the overall studies, a subgroup analysis was carried out to investigate the actual effects of types of outcome measures (i.e., center of pressure [COP] area and rate, LF_PS, and the score of DHI) (Supplementary Fig. 2 in the online-only Data Supplement). The result of this subgroup analysis was statistically significant (χ^2=9.83, df=3, p=0.02). However, the estimate of SMDs for the random effect model was -0.01 (95% CI: -0.17 to 0.14). This result should be interpreted carefully because of the existence of 0 in 95% CI. Even the estimates of the random effect model had a p-value below 0.05, while the existence of 0 in the range of 95% CI was not statistically significant [42].

Given this caution, the result for the COP area (Supplementary Fig. 2A in the online-only Data Supplement) and rate (Supplementary Fig. 2B in the online-only Data Supplement) showed the same value for SMDs of 0.09 (95% CI: -0.15 to 0.33). That is, the experimental group had not benefited from intervention (i.e., conducting vestibular rehabilitation with the VR technique). The result of LF_PS had similar findings. Even the SMDs of LF_PS were -0.01 (Supplementary Fig. 2C in the online-only Data Supplement), and while the experimental group had a better outcome, the statistical significance was not proved (95% CI: -0.49 to 0.47). DHI questionnaire (Supplementary Fig. 2D in the online-only Data Supplement) revealed the only subgroup with statistical significance (SMDs: -0.66, 95% CI: -1.10 to -0.22). This result confirmed that the experimental group had reduced their negative aspects of dizziness with support from the VR techniques.

Discussion

The current study analyzed VR and/or AR technologies being applied to the hearing loss, tinnitus, and vestibular disease. The related studies were all systematically reviewed and analyzed using a meta-analysis approach.

Hearing loss

Unfortunately, the study by Wolter, et al. [25] was only included in the present study. The authors demonstrated that the sound environment and hearing ability influenced the function of balance. They evaluated balance function using a VR simulator-based moving sound environment (i.e., real street setting) and a static sound environment for sensorineural hearing loss with bilateral vestibular loss (SNHL-BVL) children. In addition, the directionality of the sound was added to the sound environment. As expected, the SNHL-BVL children had poorer balance scores than normally developing counterparts in all conditions. With a within-group comparison, the balance score for SNHL-BVL children was not affected by either the VR simulator-based sound environment or directionality. For the effect of hearing ability, SNHL-BVL children had slightly better balance performance when their cochlear implant was activated with variables of the VR simulator-based sound environment and directionality. Results for SNHL-BVL children may have derived from the ability of spatial hearing [25,43]. That is, deteriorated spatial hearing with sensorineural hearing loss made these children insensitive to different sound flows (i.e., dynamic and static sound environments), and this insensitivity led to a similar balance performance in the various VR simulator-based sound environment. However, when their implantation was turned on, the decreased spatial hearing partially supported by the cochlear implant and the balance performance slightly increased. These results demonstrated that the VR technique may be helpful for individuals with hearing loss and balance dysfunction about hearing compensation that occurred when using hearing assistive device. Nevertheless, it is regrettable that only one study exists in this scope. We believe that the current technique will be utilized soon. Also the effect of advanced technologies as a digital therapeutics will be proved by expanding to various population in not only children with hearing loss but also the hearing-impaired adults and elderly.

Tinnitus

In our systematic search, 2 of 23 studies reported on VR-related tinnitus management. Although the field of pharmacologic approach and cognitive therapy for tinnitus is rapidly developing, there have been few treatments using VR so far.

Reporting the effect of VR techniques in the field of tinnitus therapy, the studies have been concluded in different ways. First, the study by Bertet, et al. [41] investigated the effect of virtually synthesized tinnitus on the lateralization of tinnitus. They compared three different virtual tinnitus avatars while using hearing thresholds-matched methods and pitch matching-like mixed tones method. The authors reported that the mixed tones method, by using pure-tone and narrow band noise, was the most preferred for the tinnitus patients (8 of 12 patients). This result was statistically supported by a Kolmogorov-Smirnov test, which statistically compared the visual analogue scale (VAS) of each observation. The ranking of each method revealed that method C (i.e., pitch matching-like mixed tones) had a significantly higher ranking (smaller score of VAS) than method A ($p<0.02$) and B ($p<0.002$) which was based on the hearing thresholds curve. Their results demonstrated that the VR-based tinnitus avatar could be applied to tinnitus patients, to some extent.

In the other study, Malinvaud, et al. [14] showed slightly different results even though it had the effect of VR-based therapy on tinnitus patients. The authors compared the VR-based 3D environment with auditory and visual immersion therapy to clinically conventional therapy, such as cognitive behavior therapy (CBT) for subjective tinnitus patients. They measured various outcomes including several questionnaires, e.g., the Subjective Tinnitus Severity Scale, Tinnitus Handicap Questionnaire, Tinnitus Handicap Inventory, Hospital Anxiety-Depression Scale (HAD), and VAS. The results showed that all the outcome measures were not significantly different as the time points (i.e., post treatment, 1-month follow-up, and 3-month follow-up) in both the VR and CBT groups. However, all the outcome measures had significant enhancement from the baseline to 3-month follow-up except for HAD. Rather than quickly concluding the effect of VR on tinnitus treatment through two peer-reviewed papers, thus we suggest that the treatment data should be accumulated and the most efficient VR setting and design for tinnitus patients at clinic and/or at home should be devised.

Vestibular diseases

Although most studies included in the present study were vestibular disease-related, the results of the meta-analysis could show that various outcome measures, such as COP area, COP rate, and LF_PS, were not statistically significant. The effect of the VR technique in the vestibular rehabilitation was not proved for the COP area and rate.

Notably, there was a discrepancy among the studies that reported the effect of VR-based vestibular rehabilitation [10,26-29,32,33,38]. For example, Garcia, et al. [27] demonstrated that those patients with Ménière's disease (MD) was significantly improved in terms of COP area and DHI score after being treated using VR-based vestibular rehabilitation. However, in other studies [28,29], there was no statistically significant difference between the time points, such as pre- and post- treatment for the benign paroxysmal positional vertigo patients. This discrepancy may have stemmed from aging [6,29]. Obviously, aging directly deteriorates the function of the sensory systems including sensory integration. This decreased sensory integration affected the recurrence of dizziness after treatment [29,38,44]. While the MD patients of Garcia, et al. [27] ranged from young to old adults (age ranged from 19 to 60 years), samples of the other study were middle age to older age adults [26] or adults over 60 years [28,29]. A similar pattern was also observed in other vestibular disease-related outcome measures, such as the rate of COP.

The DHI score revealed that the experimental group actually had a reduced score with VR-based rehabilitation. It was the subjective and self-report measuring method and related to the physical, functional, and emotional aspects of vestibular disease. In other words, the patients with vestibular dysfunction improved their subjective aspects when using VR techniques while being strongly supported in most studies [27,28,32,38]. In short, this result implied that the subjective measures for patients with vestibular disease could be achieved by the implementation of VR [38,45].

Limitations of the study and future directions

Although the purpose mainly was to check how much VR technology was enhanced in hearing loss, tinnitus, and vestibular disease, the present study had several limitations. First, the article search process for the current study had a limitation of not being able to include all the studies related to our purpose. While we exerted a search and select of the articles to avoid this limitation, inevitable variables, such as a lack of explicitness of related topics in the individual article. Similar to the first limitation, the other diseases, i.e., hearing loss and tinnitus, could not lead to a meta-analysis due to the small sample size. We might argue that this limitation emphasizes the diversity of the subfields in otology and audiology. One suspected answer is that the appropriate tools using recent technology are not fully developed yet for individuals with hearing loss.

It is acknowledged that auditory training is necessary and an effective tool for the hearing-impaired regardless of age [46-48], however, conventional and/or traditional auditory training has a disadvantage in terms of time, distance, and cost [46,47].

To overcome the limitation of auditory training, a simulated digital environment called 'metaverse' which immerses concept with VR, AR, and the blockchain technique could be considered. This digital world is created for interaction between users like social media and thus may play an important role for the hearing-impaired, including improvement of the social skills and the self-esteem of children.

In conclusion, the present study highlights the recent and advanced VR technologies and their applications to hearing loss, tinnitus, and vestibular disease by systematic review and meta-analysis. Although there was lack of study samples (i.e., two studies for hearing loss and one study for tinnitus), still due to the ongoing development of the technology, VR-based vestibular rehabilitation showed a positive applicability and weaken symptom, especially for subjective rating measures. Also, the negative effect of aging on vestibular disease was indirectly identified. In the future, many more clinical trials and evidence-based approach will be needed to verify the positive implementation of state-of-the-art technology in both hearing loss and tinnitus.

Supplementary Materials

The online-only Data Supplement is available with this article at https://doi.org/10.7874/jao.2022.00234.

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Conflicts of Interest

The authors have no financial conflicts of interest.

Author Contributions

Conceptualization: all authors. Data curation: Chanbeom Kwak. Formal analysis: Chanbeom Kwak. Funding acquisition: Junghwa Bahng, Woojae Han. Investigation: Woojae Han, Junghwa Bahng. Visualization: Chanbeom Kwak. Writing—original draft: Chanbeom Kwak. Writing—review & editing: Woojae Han, Junghwa Bahng. Approval of final manuscript: all authors.

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