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# Can virtual reality replace conventional vestibular rehabilitation tools in multisensory balance exercises for vestibular disorders? A non-inferiority study

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## Abstract

**Background** Vestibular rehabilitation uses multisensory balance exercises to optimize the integration and weighting of sensory inputs, including visual, vestibular, and proprioceptive signals. Head-mounted displays (HMDs) have emerged as a promising tool for these exercises, offering the ability to generate unreliable or conflicting visual stimuli, thereby enhancing vestibular and proprioceptive input weighting. This study aimed to determine whether a virtual reality (VR)-based rehabilitation program using HMDs is non-inferior to a conventional program employing an optokinetic stimulator and slaved environmental surround for multisensory balance exercises.

**Methods** Seventy-six participants with vestibular disorders were randomized into either the VR-based or conventional rehabilitation program for three weeks in a randomized controlled non-inferiority trial with blinded assessment. The non-inferiority margin was set at 5% of the control group's score. Both programs were multidisciplinary and included multisensory balance exercises designed to challenge sensory re-weighting. The primary outcome was the stability score, measured with eyes closed on an unstable platform using posturography, to evaluate postural control. Secondary outcomes included other variables from posturography, perceived disability assessed using the Dizziness Handicap Inventory (DHI), and tolerance to the multisensory balance exercises with unreliable or conflicting visual stimuli, assessed using the Simulator Sickness Questionnaire (SSQ).

**Results** The results showed that multisensory balance exercises with unreliable or conflicting visual stimuli were well tolerated in both groups, as indicated by low SSQ scores. Both rehabilitation programs led to significant pre-post improvements in postural control and perceived disability. However, the VR program did not meet the non-inferiority criterion compared to the conventional program. The primary outcome analysis revealed a difference of − 13.36 (95% CI − 29.84 to 3.11), with the lower bound of the confidence interval (− 29.84) falling below the non-inferiority margin of -2.01. Similarly, secondary outcomes, including other variables from posturography and the DHI, also failed to meet the non-inferiority criterion.

**Conclusion** Although VR rehabilitation shows innovative potential for multisensory balance training, its effectiveness was not demonstrated to be non-inferior to the conventional approach. Therefore, we recommend considering

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it as a complementary tool rather than a primary device for vestibular rehabilitation. Further research is needed to enhance the efficacy of VR-based rehabilitation for vestibular disorders while maintaining its tolerance.

*Trial registration* NCT03838562.

## Background

Vertigo, dizziness, and imbalance are common conditions in the general population, with their prevalence increasing with age [1]. Approximately 30% of individuals over 60 report experiencing vestibular disorders at some point in their lives [2]. These disorders often lead to a re-weighting of sensory inputs, favoring visual cues over vestibular and proprioceptive signals [3]. However, this compensation can cause dizziness and imbalance, particularly in environments where visual cues are unreliable or conflicting, such as in darkness, crowds, or supermarkets [4]. Patients may rely on inaccurate visual information to orient themselves, exacerbating their symptoms [5]. These disorders significantly increase the risk of falls, loss of independence, and reduced quality of life [6].

Vestibular rehabilitation aims to optimize and accelerate recovery or compensation for vestibular disorders [7]. This targeted approach helps improve balance, stabilize gaze, enhance quality of life, and reduce symptoms like dizziness and vertigo, enabling patients to resume daily activities [8–10]. Effective balance control relies on multisensory integration, combining vestibular, visual, and proprioceptive inputs. Vestibular rehabilitation incorporates exercises designed to train balance in environments with altered or conflicting visual inputs, such as those using optokinetic stimulator in a dark room or a slaved environmental surround [8, 10]. The goal is to help patients adapt by relying on the most appropriate sensory input for each context, rather than depending predominantly on vision [7].

In recent years, virtual reality (VR) has emerged as a promising tool for vestibular rehabilitation. Head-mounted displays (HMDs) provide a high level of immersion in virtual environments that are easily manipulated, varied, and closely mimic real-life situations, often incorporating playful elements [11]. This technology is particularly well-suited for exercises involving unreliable or conflicting visual input. Recent systematic reviews suggest that integrating VR into vestibular rehabilitation offers advantages over programs without VR [12, 13]. However, when used alone, VR has not demonstrated clear superiority over conventional approaches [14, 15].

Despite these limitations, VR stands out for its unique practical benefits. Beyond being engaging, well-accepted by patients [16], and easy to use [17], VR offers the additional advantages of portability and minimal space requirements—unlike traditional tools such as optokinetic stimulators, which require a dedicated dark room, or large, expensive slaved environmental surrounds. These features make VR an attractive alternative to conventional vestibular rehabilitation tools.

Building on this, we are investigating the potential of VR to replace traditional equipment for improving postural control in patients with vestibular disorders. We propose a non-inferiority comparative study, comparing vestibular rehabilitation using VR to the conventional approach of a rehabilitation program with an optokinetic stimulator and slaved environmental surround for multisensory balance exercises. The primary aim of this study is to determine whether the VR rehabilitation program is non-inferior to the conventional rehabilitation program in improving balance in patients with vestibular syndrome after three weeks of rehabilitation. A non-inferiority margin of 5% of the control group's score was chosen based on normative data variability to ensure clinical relevance and preserve the utility of VR rehabilitation. Secondary objectives include evaluating whether the VR program is non-inferior in reducing perceived disability related to vertigo, dizziness, and instability, as well as assessing the tolerability of the VR program.

## Method

The study was designed as a pragmatic, prospective, randomized, controlled, non-inferiority, single-center, two-arm, parallel trial, with blinded assessment after three weeks of rehabilitation and three-month follow-up.

### Participants

This study protocol was approved by the ethics committee *Sud-Est V* of Grenoble University Hospital Center (ID RCB: 2018-A02247-48), France. Participants were recruited from patients hospitalized in the rehabilitation department of Paul Coste Floret Hospital (Lamalou-les-Bains, France), between April 2019 and November 2023, with follow-up completed in April 2024. The inclusion criteria were adults (≥ 18 years old) hospitalized for symptoms related to a vestibular disorder, eligible for a rehabilitation program, able to stand unaided, informed about the study, who had provided written consent, and were covered by a social security system.

Exclusion criteria included poor vision or blindness (acuity < 1/10), lack of depth perception, severe strabismus, oculomotor disorders, a history of epilepsy, severely impaired general health, pregnancy, and individuals

protected by law or deprived of liberty. To improve study recruitment, we removed two initial exclusion criteria (bilateral vestibular loss and hydropic disease). However, randomization was stratified based on these factors, as described below.

#### Randomization

The study investigator used a 1:1 randomization ratio, with blocking in groups of 4 and 6, stratified by whether the pathology was acute or chronic (lasting more than three months) and whether the patient had bilateral vestibulopathy or hydropic disease, to ensure balanced patient distribution across groups. The randomization process was conducted online via the eCRF in the Ennov Clinical® software. Patients and therapists involved in the rehabilitation could not be blinded due to the nature of the intervention. However, the investigator who performed the randomization also ensured that an evaluator, who was blinded to the randomization group, was selected to assess outcomes in the post-intervention evaluations in order to minimize the risk of evaluator bias affecting the outcome measures.

#### Intervention

All participants followed a three-week personalized rehabilitation program conducted five days a week. This program included vestibular physiotherapy provided by physiotherapists trained in vestibular rehabilitation, group balance circuits led by occupational therapists, and physical activity sessions supervised by Adapted Physical Activity specialists. Additionally, orthoptic, psychomotor therapy and psychotherapeutic therapy were provided as needed (see supplementary Table 1 for details of the rehabilitation program).

The rehabilitation program was identical in both groups, except for the multisensory balance exercises, where the physiotherapist tailored challenges to the participant's postural control in the presence of unreliable or conflicting visual input.

In the experimental group, a head-mounted display (HTC Vive®, Taiwan, China) was used in combination with software (Virtualis®, Montpellier, France) to project 360° virtual moving environments, with the direction and velocity controlled by the therapist. This setup enabled various exercises, including postural control tasks with circular optokinetic stimulation (rotational movement of the environment) or radial stimulation (linear scrolling movement), both of which created an illusion of environmental movement. Additional exercises involved environments slaved to head movements, thereby generating an unreliable or conflicting visual environment.

In the control group, postural control exercises were conducted in a darkened room with an optokinetic stimulator (Stimulopt, Framiral®, Grasse, France) projecting moving points of light onto the walls, floor, and ceiling, with the direction and velocity controlled by the therapist, creating an illusion of environmental movement. Additional postural control exercises were performed on the Neurocom® Smart Equitest®, where the environmental cabin could be slaved to the movement of the patient's center of pressure in the sagittal plane, thus creating an unreliable or conflicting visual environment.

#### Outcomes

Posturographic measurements were performed before and after the rehabilitation program. The main outcome is the score of stability measured eyes closed on an unstable platform (condition E) on the Balance Quest System (Framiral®, Grasse, France) after three weeks of personalized vestibular rehabilitation. The results were expressed as percentages, with 0% indicating sway exceeding the limit of stability (fall) and 100% indicating perfect stability. The formula used was:

$$\theta = \left[\frac{(100 - \sigma x)}{100}\right] \times \left[\frac{(100 - \sigma y)}{100}\right]$$

where σx, σy represent the standard deviations in anterior—posterior and lateral direction and ranged from 0 to 100 mm [18].

The secondary outcomes are:

The score of stability measured as above on the Balance Quest System in condition A: eyes open, stable platform, B: eyes closed, stable platform, C: eyes open, stable platform, optokinetic stimulation, D: eyes open, unstable platform, F: eyes open, unstable platform, optokinetic stimulation.

The Postural Instability Index (PII) was calculated from posturographic data collected using the Balance Quest System under different conditions. The PII was computed based on both the spectral power within specific frequency ranges (F1: 0.05 Hz to 0.5 Hz, F2: 0.5 Hz to 1.5 Hz, and F3: 1.5 Hz to 10 Hz) and the total time during which the spectral power of body sway frequencies within these ranges was attenuated by postural control mechanisms. The formula used was:

$$\mathrm{PII} = \sum \mathrm{x} \sum \mathrm{y} \frac{SP(F1, F2, F3)}{TC(F1, F2, F3)}$$

where **SP** represents the spectral power, and **TC** represents the time of cancellation for each of the three frequency bands [19].

The Dizziness Handicap Inventory (DHI) is a 25-item self-report questionnaire designed to assess the impact of dizziness on daily life by measuring self-perceived disability. The version used in this study had five response

options: 0 (no, never), 1 (rarely), 2 (sometimes), 3 (often), and 4 (yes, always). The total score ranges from 0 to 100, with higher scores indicating greater perceived disability. Three sub-scores were calculated: Functional (9 questions, 36 points), Emotional (9 questions, 36 points), and Physical (7 questions, 28 points) [20]. The DHI was completed by participants before, just after and 3 months after the rehabilitation program for follow-up.

The Simulator Sickness Questionnaire (SSQ) is a 16-item self-report questionnaire designed to assess the side effects of virtual reality, with items rated from 0 (none) to 3 (severe). The total score ranges from 0 to 48, with higher scores indicating more severe symptoms. Two sub-scores were calculated: Nausea (9 items, 27 points) and Oculomotor (7 items, 21 points) [21]. The SSQ was administered to both groups: in the experimental group to evaluate the tolerability of virtual reality, and in the control group, as optokinetic stimulation and the slaved environmental surround could provoke similar symptoms to simulator sickness. The SSQ questionnaire was completed by the participants at the end of each week of the rehabilitation program.

### Sample size

We expect no difference between the two groups (0 points). The normative value for the primary endpoint, provided by the manufacturer, is 88.7 (standard deviation 6.9). We set a non-inferiority margin of 4.435 points (i.e., 5% of 88.7). The non-inferiority margin was set at 5% of the normative value of the primary outcome to ensure that the experimental group would not be considered inferior by more than one standard deviation, while maintaining clinical relevance. To demonstrate the non-inferiority of the Virtual Reality group, with a 5% alpha risk and 80% power, 31 patients per group are required. Accounting for a 20% drop-out rate, 38 patients per group will need to be recruited (calculation performed in SAS).

### Data analysis

Statistical analysis was conducted using the SAS 9.4 (SAS Institute, Cary, NC, USA) and R version 4.3.

#### *Descriptive analysis*

A descriptive analysis of the population was conducted, with continuous variables reported as means and standard deviations, and qualitative variables presented as counts and percentages.

#### *Study population*

The analysis was performed on two populations: the per-protocol (PP) population, which included all participants who attended at least 80% of the vestibular physiotherapy sessions and completed the post-intervention assessments, and the modified intention-to-treat (mITT) population, which included all participants who completed a valid assessment of the outcomes.

#### *Main analysis*

A non-inferiority analysis was conducted to compare the Balance Quest System stability score in Condition E between the two groups performed during the post-intervention assessments. The difference in scores, along with its 95% confidence interval, was calculated.

The primary analysis was conducted on the PP population, with the same analysis subsequently performed on the mITT population. In both populations, the experimental program was considered non-inferior to the control program if the lower bound of the 95% confidence interval was above the non-inferiority threshold, defined as 5% of the control group's score at the post-intervention assessment.

#### *Secondary analysis*

The same non-inferiority analysis was conducted to compare the stability score, the PII across all conditions, and the DHI questionnaire between the two groups at the post-intervention assessments. For the stability score, where a higher value indicates better stability, non-inferiority was demonstrated if the lower bound of the 95% confidence interval was above the non-inferiority threshold. Conversely, for the PII and DHI, where lower values indicate better stability (PII) and less disability (DHI), non-inferiority was demonstrated if the upper bound of the 95% confidence interval was below the non-inferiority threshold.

A non-inferiority sensitivity analysis was performed to compare the evolution of variables between the two groups pre- and post-intervention.

A longitudinal analysis of scores pre-intervention, post-intervention, and at the three-month follow-up was conducted in the mITT population, including participants from both groups combined. A Kruskal–Wallis test was used for the DHI score, and Wilcoxon signed rank tests, corrected by the FDR method, were used for pairwise comparisons of the DHI and posturographic variables (without FDR correction for the latter).

Finally, a safety analysis was conducted in both groups to evaluate the tolerability of postural control exercises performed under conditions with unreliable or conflicting visual input.

## Results

### Population characteristics

Seventy-six participants were included and randomized (38 in each group). Two participants from each group

were excluded from the modified intention-to-treat analysis because they did not complete the post-intervention assessments. Additionally, two participants in the control group and four in the virtual reality group were excluded from the per-protocol analysis due to attending fewer than 80% of the vestibular physiotherapy sessions. One other participant was excluded in the virtual reality group because the rehabilitation program was interrupted for six months due to Covid-19-related confinement. The flow chart is presented in Fig. 1. Demographic and health related characteristics of PP and mITT population are presented in Table 1.

During the 3-week rehabilitation program, participants engaged in exercises specifically focused on vestibular rehabilitation, including 30.1 ± 3.6 physiotherapy sessions lasting 30 min each, with 83.0 ± 66.4 min dedicated to multisensory balance exercises performed under unreliable or contradictory visual information. Additionally, they participated in 13.2 ± 4.1 group balance circuit sessions, each lasting 60 min, and 2.7 ± 1.8 sessions of 30-min orthoptic exercises.

### Primary outcome analysis

The primary outcome analysis using both PP and mITT sets showed that the difference between the experimental and control groups was -13.36 (95% CI − 29.84 to 3.11) in the PP analysis and -10.92 (95% CI − 26.8 to 4.97) in the mITT analysis (Fig. 2). The non-inferiority hypothesis was rejected in both analyses, as the lower bound of the 95% confidence interval fell below the predefined non-inferiority margin of − 2.01 (corresponding to 5% of the Balance Quest System Condition E stability score of the control group).

### Sensitivity analysis of the primary outcome

Sensitivity analysis based on score changes between pre and post-intervention assessment showed that the difference between the experimental and control groups was − 6.03 (95% CI − 22.44 to 10.37) in the PP analysis and − 3.83 (95% CI − 19.08 to 11.42) in the mITT analysis. Once again, the non-inferiority hypothesis was rejected, as the lower bound of the 95% confidence interval was below the predefined non-inferiority margin of − 1.18 and − 1.12, respectively (see Table 2).

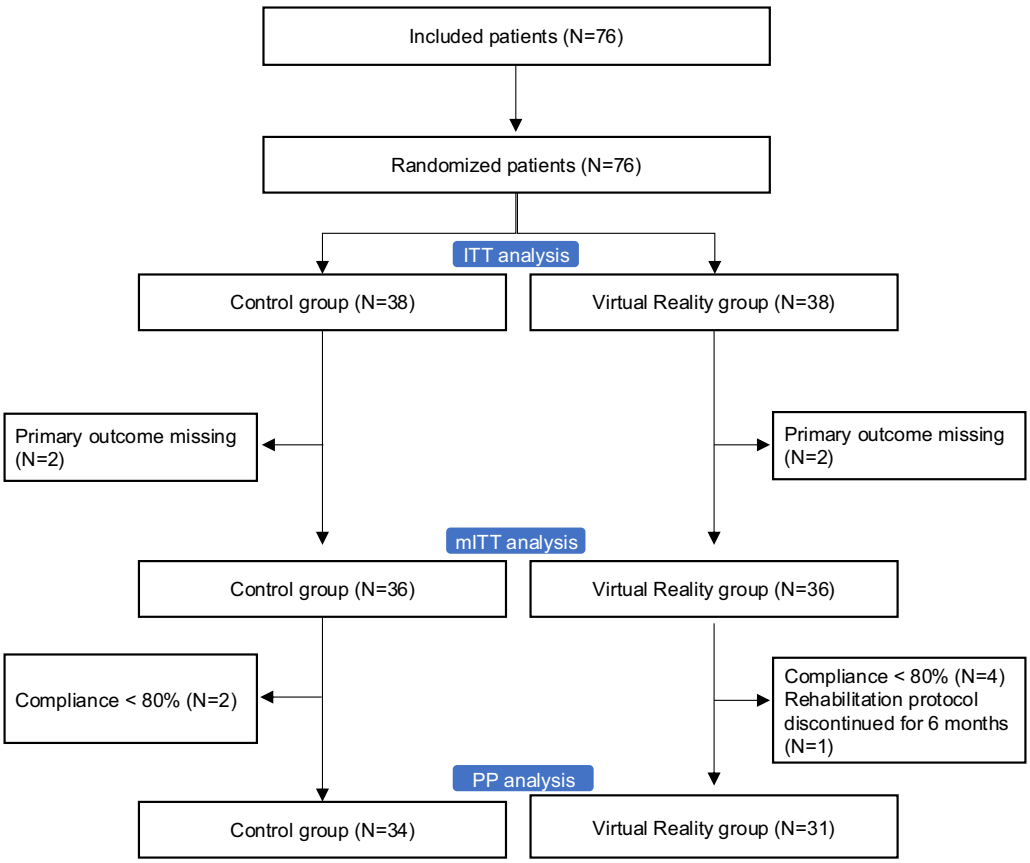


**Fig. 1** Flow Chart and Analysis Population

**Table 1** Per-protocol and modified Intention-To-Treat population baseline characteristics

| Variable | PP population | | mITT population | |
|---|---|---|---|---|
| | Virtual Reality, N = 31 | Control, N = 34 | Virtual Reality, N = 36 | Control, N = 36 |
| Sex, n (%) | | | | |
| Female | 16 (51.61) | 23 (67.65) | 19 (52.78) | 24 (66.67) |
| Male | 15 (48.39) | 11 (32.35) | 17 (47.22) | 12 (33.33) |
| Age | | | | |
| Mean (± SD) | 67.94 (± 11.03) | 67.53 (± 14.13) | 67.75 (± 11.54) | 66.44 (± 15.54) |
| BMI (kg/m$^2$) | | | | |
| Mean (± SD) | 26.94 (± 5.50) | 26.13 (± 5.08) | 26.72 (± 5.27) | 26.07 (± 5.13) |
| Missing | 1 | 0 | 1 | 0 |
| Vestibular disorders, n (%) | | | | |
| Unilateral Vestibulopathy | 7 (22.58) | 12 (35.29) | 9 (25.00) | 13 (36.11) |
| Bilateral Vestibulopathy | 9 (29.03) | 7 (20.59) | 9 (25.00) | 8 (22.22) |
| Functionals | 13 (41.94) | 14 (41.18) | 15 (41.67) | 14 (38.89) |
| Others | 2 (6.45) | 1 (2.94) | 3 (8.33) | 1 (2.78) |
| Duration of vestibular disorders, n (%) | | | | |
| Less than 3 months (Acute) | 2 (6.45) | 2 (5.88) | 3 (8.33) | 3 (8.33) |
| More than 3 months (chronic) | 29 (93.55) | 32 (94.12) | 33 (91.67) | 33 (91.67) |
| Balance quest system | | | | |
| Condition A | | | | |
| Stability (/100) Mean (± SD) | 88.90 (± 8.70) | 88.56 (± 8.44) | 89.03 (± 8.32) | 88.86 (± 8.29) |
| PII Mean (± SD) | 2.56 (± 0.97) | 2.43 (± 1.20) | 2.54 (± 0.98) | 2.36 (± 1.21) |
| Condition B | | | | |
| Stability (/100) Mean (± SD) | 81.42 (± 18.68) | 77.74 (± 27.71) | 82.08 (± 17.69) | 78.64 (± 27.18) |
| PII Mean (± SD) | 3.17 (± 1.06) | 3.03 (± 1.35) | 3.11 (± 1.06) | 2.95 (± 1.36) |
| Condition C | | | | |
| Stability (/100) Mean (± SD) | 45.29 (± 40.03) | 52.09 (± 42.22) | 47.36 (± 39.52) | 54.14 (± 41.90) |
| PII Mean (± SD) | 4.69 (± 0.97) | 4.08 (± 1.44) | 4.62 (± 0.97) | 4.01 (± 1.49) |
| Missing PII | 2 | 3 | 2 | 3 |
| Condition D | | | | |
| Stability (/100) Mean (± SD) | 60.35 (± 31.76) | 63.00 (± 31.12) | 62.58 (± 30.16) | 63.56 (± 30.44) |
| PII Mean (± SD) | 4.38 (± 1.15) | 4.31 (± 1.10) | 4.35 (± 1.11) | 4.28 (± 1.14) |
| Condition E | | | | |
| Stability (/100) Mean (± SD) | 9.26 (± 21.64) | 16.59 (± 30.79) | 10.67 (± 22.30) | 17.75 (± 31.59) |
| PII Mean (± SD) | 5.55 (± 0.44) | 5.14 (± 0.68) | 5.53 (± 0.48) | 5.10 (± 0.71) |
| Missing PII | 9 | 2 | 9 | 3 |
| Condition F | | | | |
| Stability (/100) Mean (± SD) | 4.39 (± 13.70) | 6.41 (± 21.24) | 3.78 (± 12.78) | 7.83 (± 22.79) |
| PII Mean (± SD) | 5.73 (± 0.38) | 5.35 (± 0.68) | 5.81 (± 0.40) | 5.30 (± 0.40) |
| Missing PII | 16 | 14 | 18 | 15 |
| DHI | | | | |
| Total score (/100) Mean (± SD) | 52.13 (± 19.17) | 46.44 (± 21.29) | 51.53 (± 19.95) | 46.67 (± 20.94) |
| Physical sub-score/28 Mean (± SD) | 15.94 (± 7.27) | 14.91 (± 6.66) | 15.61 (± 7.22) | 14.94 (± 6.85) |
| Emotional sub-score/36 Mean (± SD) | 17.03 (± 6.28) | 14.00 (± 8.46) | 16.89 (± 7.12) | 14.19 (± 8.26) |
| Functional sub-score/36 Mean (± SD) | 19.16 (± 7.74) | 17.53 (± 8.33) | 19.02 (± 7.66) | 17.53 (± 8.13) |

*DHI* Dizziness Handicap Inventory, *mITT* modified Intention-To-Treat, *PII* Postural Instability Index, *PP* Per-Protocol, *SD* Standard Deviation

### Secondary outcomes analysis

For the secondary outcomes analysis at the post-intervention assessments, using both PP and mITT sets, the non-inferiority hypothesis was rejected for all variables (Balance Quest System stability score and PII in conditions A, B, C, D, and F, as well as the DHI score and

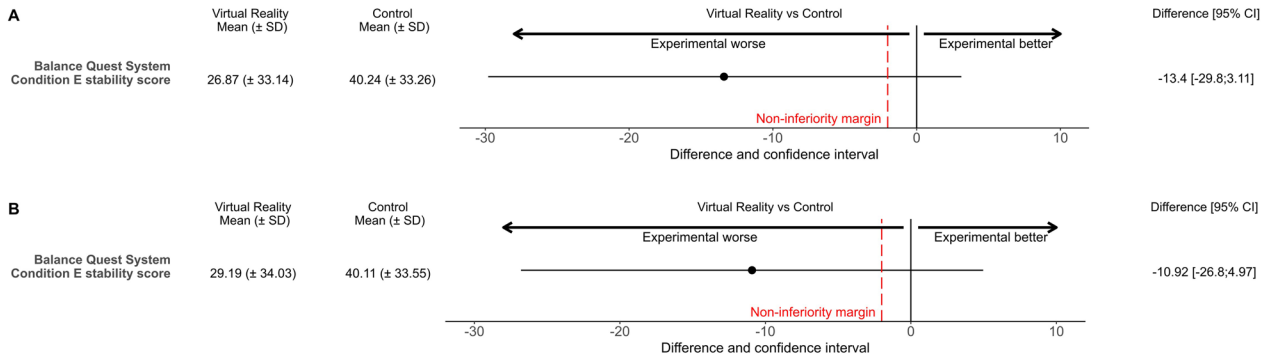


**Fig. 2** Non-inferiority results for the primary outcomes using PP analysis (**A**) and mITT analysis (**B**). The mean scores and standard deviations for each group are shown on the left, while the differences between groups and their 95% confidence intervals are displayed on the right. To support the non-inferiority hypothesis, the lower bound of the 95% confidence interval of the differences must be above the non-inferiority margin

**Table 2** Sensitivity analysis results of the primary outcome in PP and mITT analysis

| Difference (pre-post) balance quest condition E | N | Experimental | N | Control | Difference between groups (95% CI) | Non inferiority margin |
|---|---|---|---|---|---|---|
| PP population | 31 | 17.61 (± 31.52) | 34 | 23.65 (± 34.40) | − 6.03 (− 22.44; 10.37) | − 1.18 |
| mITT population | 36 | 18.53 (± 30.98) | 36 | 22.36 (± 33.83) | − 3.83 (− 19.08; 11.42) | − 1.12 |

*CI* Confidence Interval, *mITT* modified Intention-To-Treat, *PP* Per-Protocol

its sub-scores), except the stability score in condition A. In this condition, the difference between the groups was 0.45 (95% CI − 3.97 to 4.86) in the PP analysis and 0.58 (95% CI − 3.43 to 4.60) in the mITT analysis, with margins of − 4.45 and − 4.46, respectively (See Table 3 for details). The DHI was also assessed at the 3-month follow-up after the intervention. The analysis revealed a difference between groups of − 0.4 (95% CI − 13.82 to 13.02) in the PP analysis and 0.6 (95% CI − 12.22 to 13.43) in the mITT analysis. The non-inferiority hypothesis was rejected in both analyses, as the upper bound of the 95% confidence interval was above the predefined non-inferiority margins of 1.99 and 1.98, respectively. In the sensitivity analysis, the non-inferiority hypothesis was also rejected in both analyses for all variables (see supplementary material).

### Longitudinal analysis

The comparative analysis of the DHI total score and subscore at pre-intervention, post-intervention, and follow-up, conducted on the combined mITT population from both groups, demonstrated a significant effect of rehabilitation ($p < 0.001$) (Fig. 3).

The comparative analyses of the posturographic variables at pre- and post-intervention conducted on the combined mITT population from both groups, demonstrated a significant increase in the stability score under conditions C, D, E, and F ($p < 0.001$, $p = 0.002$, $p < 0.001$, $p < 0.001$). Additionally, there was a significant improvement in the Postural Instability Index (PII) in conditions C, D, and E ($p < 0.001$; $p < 0.001$; $p = 0.006$). No significant differences were found for the stability score and PII in conditions A and B, nor for PII in condition F.

### Safety analysis

The SSQ scores for the experimental and control groups were 8.83 ± 8.69 and 12.65 ± 7.76, respectively, after the first week of rehabilitation; 10.27 ± 10.28 and 11.50 ± 7.73 after the second week; and 9.48 ± 9.83 and 10.45 ± 8.25 after the final week. No significant differences were observed between groups or across time points.

## Discussion

This study tested the non-inferiority hypothesis of a vestibular rehabilitation program using VR compared to a conventional rehabilitation program. Specifically, we aimed to determine whether VR with head-mounted displays could replace conventional tools like optokinetic stimulators and slaved environmental surrounds during multisensory balance exercises involving unreliable or conflicting visual input. Contrary to our hypothesis, our results indicate that improvements in postural control and perceived disability in patients with vestibular disorder were not equivalent between the two groups. More precisely, we were unable to demonstrate the

**Table 3** Secondary outcomes results in PP and mITT analysis

| **PP analysis** | **Experimental, N = 31** | **Control, N = 34** | **Difference between groups (95% CI)** | **Non inferiority Margin** |
|---|---|---|---|---|
| Balance quest system | | | | |
| Condition A | | | | |
| Stability (/100) Mean (± SD) | 89.38 (± 8.67) | 88.93 (± 9.11) | 0.45 (– 3.97;4.86) | – 4.4465 |
| PII Mean (± SD) | 2.39 (± 0.94) | 2.33 (± 1.09) | 0.06 (– 0.45;0.56) | 0.1165 |
| Condition B | | | | |
| Stability (/100) Mean (± SD) | 84.35 (± 19.44) | 81.44 (± 23.09) | 2.91 (– 7.72;13.55) | – 4.072 |
| PII Mean (± SD)<br>Missing PII | 2.76 (± 1.11)<br>1 | 2.96 (± 1.34)<br>0 | – 0.2 (– 0.82;0.42) | 0.148 |
| Condition C | | | | |
| Stability (/100) Mean (± SD) | 78.13 (± 23.74) | 77.88 (± 26.62) | 0.25 (– 12.3;12.79) | – 3.894 |
| PII Mean (± SD) | 3.53 (± 1.28) | 3.45 (± 1.36) | 0.08 (– 0.57;0.74) | 0.1725 |
| Condition D | | | | |
| Stability (/100) Mean (± SD) | 64.45 (± 33.33) | 72.94 (± 24.98) | – 8.49 (– 23.01;6.03) | – 3.647 |
| PII Mean (± SD)<br>Missing PII | 3.98 (± 1.19)<br>1 | 3.79 (± 1.14)<br>0 | 0.19 (– 0.4;0.77) | 0.1895 |
| Condition E | | | | |
| Stability (/100) Mean (± SD) | 26.87 (± 33.14) | 40.24 (± 33.26) | – 13.36 (– 29.84;3.11) | – 2.012 |
| PII Mean (± SD)<br>Missing PII | 5.19 (± 0.67)<br>3 | 4.98 (± 0.70)<br>0 | 0.21 (-0.14;0.56) | 0.249 |
| Condition F | | | | |
| Stability (/100) Mean (± SD) | 15.58 (± 27.26) | 29.68 (± 32.68) | – 14.10 (– 29.09;– 0.90) | – 1.484 |
| PII Mean (± SD)<br>Missing PII | 5.52 (± 0.54)<br>4 | 5.22 (± 0.65)<br>1 | 0.29 (– 0.02;0.6) | 0.261 |
| DHI | | | | |
| Total score (/100) Mean (± SD) | 36.03 (± 17.26) | 31.85 (± 19.20) | 4.18 (– 4.9;13.26) | 1.5925 |
| Physical sub-score /28 Mean (± SD) | 11.42 (± 5.44) | 10.79 (± 7.08) | 0.63 (– 2.53;3.78) | 0.5395 |
| Emotional sub-score / 36 Mean (± SD) | 11.23 (± 6.78) | 9.21 (± 5.92) | 2.02 (– 1.13;5.17) | 0.4605 |
| Functional sub-score /36 Mean (± SD) | 13.39 (± 7.07) | 11.85 (± 7.49) | 1.53 (– 2.08;5.15) | 0.5925 |
| **mIIT analysis** | **Experimental, N = 36** | **Control, N = 36** | **Difference between groups (95% CI)** | **Margin** |
| Balance quest system | | | | |
| Condition A | | | | |
| Stability (/100) Mean (± SD) | 89.77 (± 8.15) | 89.19 (± 8.91) | 0.58 (– 3.43;4.6) | – 4.4595 |
| PII Mean (± SD) | 2.35 (± 0.92) | 2.29 (± 1.07) | 0.06 (– 0.41;0.53) | 0.1145 |
| Condition B | | | | |
| Stability (/100) Mean (± SD) | 84.50 (± 18.33) | 82.06 (± 22.57) | 2.44 (– 7.22;12.11) | – 4.103 |
| PII Mean (± SD)<br>Missing PII | 2.79 (± 1.07)<br>1 | 2.91 (± 1.32)<br>0 | – 0.12 (– 0.69;0.45) | 0.1455 |
| Condition C | | | | |
| Stability (/100) Mean (± SD) | 78.17 (± 22.35) | 78.67 (± 26.06) | – 0.5 (– 11.91;10.91) | – 3.9335 |
| PII Mean (± SD) | 3.66 (± 1.27) | 3.40 (± 1.35) | 0.25 (– 0.36;0.87) | 0.17 |
| Condition D | | | | |
| Stability (/100) Mean (± SD) | 65.14 (± 33.63) | 71.28 (± 27.24) | – 6.14 (– 20.53;8.24) | – 3.564 |
| PII Mean (± SD)<br>Missing PII | 3.92 (± 1.22)<br>1 | 3.81 (± 1.20)<br>0 | 0.11 (-0.46;0.68) | 0.1905 |
| Condition E | | | | |
| Stability (/100) Mean (± SD) | 29.19 (± 34.03) | 40.11 (± 33.55) | – 10.92 (– 26.8;4.97) | -2.055 |
| PII Mean (± SD)<br>Missing PII | 5.12 (± 0.65)<br>3 | 4.97 (± 0.76)<br>0 | 0.15 (-0.19;0.49) | 0.2485 |

**Table 3** (continued)

| mIIT analysis | Experimental, N = 36 | Control, N = 36 | Difference between groups (95% CI) | Margin |
|---|---|---|---|---|
| Condition F | | | | |
| Stability (/100) Mean (± SD) | 16.69 (± 27.68) | 29.81 (± 32.64) | − 13.11 (− 27.34;1.12) | − 1.4905 |
| PII Mean (± SD) | 5.53 (± 0.51) | 5.22 (± 0.67) | 0.31 (0.01;0.61) | 0.261 |
| Missing PII | 6 | 1 | | |
| DHI | | | | |
| Total score (/100) Mean (± SD) | 35.94 (± 18.19) | 32.06 (± 18.72) | 3.89 (− 4.79;12.57) | 1.603 |
| Physical sub-score /28 Mean (± SD) | 11.50 (± 5.52) | 10.69 (± 6.92) | 0.81 (− 2.14;3.75) | 0.5345 |
| Emotional sub-score/36 Mean (± SD) | 11.08 (± 6.81) | 9.53 (± 5.98) | 1.56 (− 1.46;4.57) | 0.4765 |
| Functional sub-score/36 Mean (± SD) | 13.36 (± 7.69) | 11.83 (± 7.39) | 1.53 (− 2.02;5.07) | 0.5915 |

*DHI* Dizziness Handicap Inventory, *mITT* modified Intention-To-Treat, *PII* Postural Instability Index, *PP* Per-Protocol, *SD* Standard Deviation

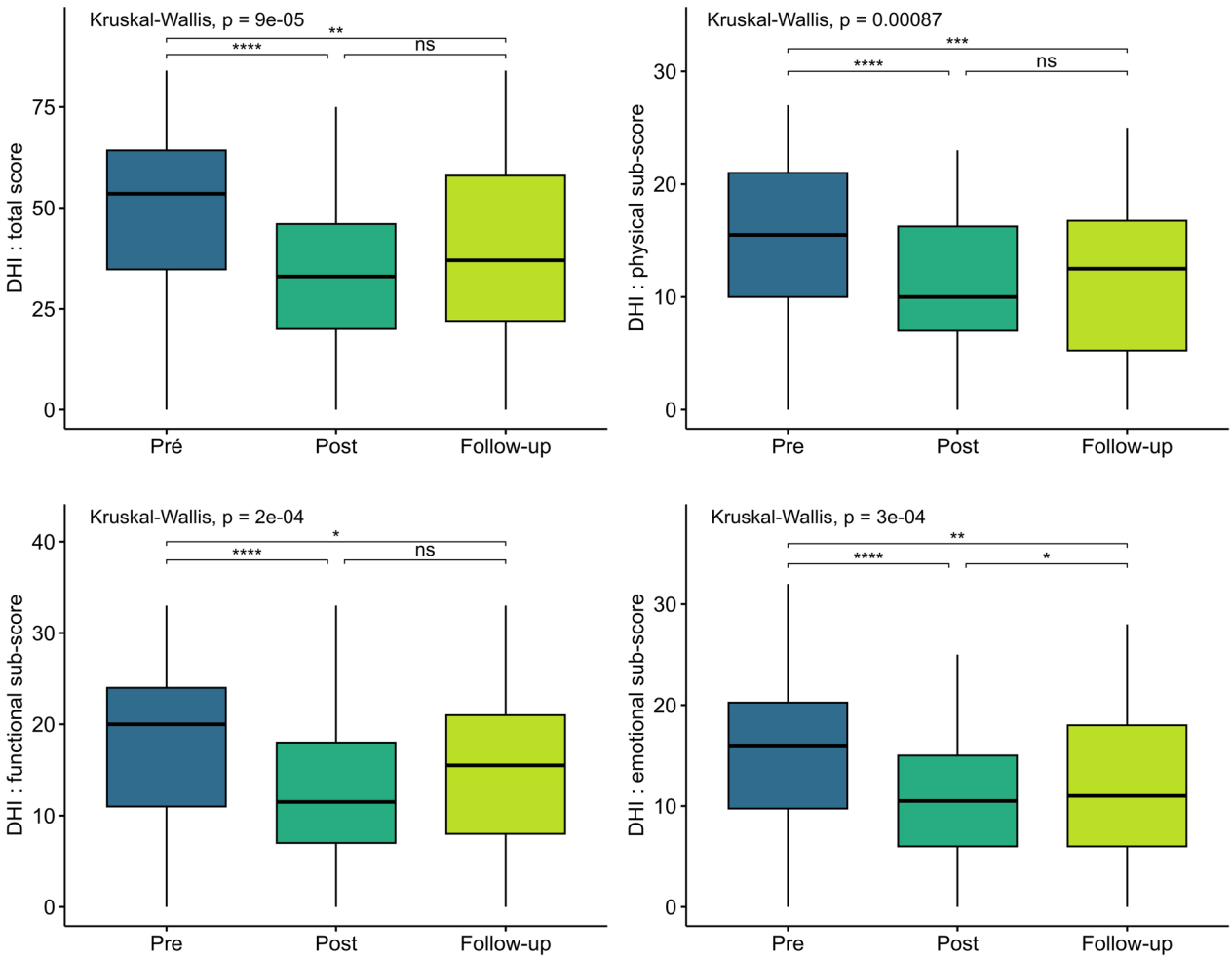


**Fig. 3** Boxplots of the Dizziness Handicap Inventory (DHI) total score and sub-scores at pre-intervention (blue), post-intervention (green), and follow-up (light green), based on the combined mITT population from both groups. The total score is displayed in the top-left panel, the physical sub-score in the top-right panel, the functional sub-score in the bottom-left panel, and the emotional sub-score in the bottom-right panel

non-inferiority of the vestibular rehabilitation program using VR compared to the conventional program.

Although VR is considered a promising tool when used as an adjunct to vestibular rehabilitation [22–24], a recent study by Piette et al. [25] highlighted an increase in center of pressure distance between posturographic recordings taken in a real-world context compared to the same context simulated in VR. This suggests that VR, while immersive and capable of reproducing realistic environments, may not fully capture the complexity of real-world visual and sensory input during balance exercises. Consequently, postural reactions in real-world conditions may differ significantly from those in VR. This discrepancy might help explain why our results showed that VR could not replace conventional tools, such as optokinetic stimulators and slaved environmental surrounds. Interestingly, the same research team has proposed a potential improvement. Their study demonstrated that the introduction of a first-person avatar representing the individual can reduce instability in virtual reality conditions. This avatar enhances the sense of embodiment, leading to a deeper immersion in the virtual environment and potentially improving the effectiveness of VR in vestibular rehabilitation [25, 26].

So, even if VR offers many advantages, including being engaging and well-accepted by patients [16], usable [17], offering a wide range of possibilities, and being portable with minimal space requirements, our results suggest that VR should remain an adjunct to conventional vestibular rehabilitation, enriching the necessary diversity of exercises [27].

In addition, our results confirm that vestibular rehabilitation significantly improves postural control, as measured by computerized dynamic posturography, and reduces the perception of disability, as measured by the DHI questionnaire, in patients with vestibular disorders [8–10]. Moreover, we demonstrated that VR was well tolerated by patients, with low SSQ scores observed in both groups. The physiotherapists in our study were well informed about the risk of cybersickness [28] and tailored the dose and intensity of VR exercises to each patient's tolerance.

The study's limitations include the non-double-blind design. Since we compared conventional devices with VR to produce unreliable or conflicting visual input, it was not possible to blind participants or therapists. We mitigated this bias by using a blinded final evaluator who was unaware of the patients' group allocation.

Another limitation of our study is that the results are based on an intensive multidisciplinary rehabilitation program, which may not always be accessible to all patients with vestibular disorders. However, as both groups followed the same program, the inability to demonstrate non-inferiority should not be influenced by this factor.

Thirdly, our sample predominantly consisted of patients with chronic vestibular disorders, exhibiting heterogeneity (unilateral, bilateral, and functional disorders). Future studies should explore whether VR might be more effective in specific subpopulations, such as those with acute unilateral vestibular disorders.

Finaly, the pragmatic design of the study could also be considered a limitation, as exercises, dosage, and intensity may have varied between participants and groups. We controlled for this by recording compliance and session durations, and conducting a per-protocol analysis, including only those who completed at least 80% of their sessions. However, confounding variables may still have influenced our results. Nonetheless, we believe this pragmatic approach reflects current clinical practice and is suitable for evaluating the potential of VR to replace conventional vestibular rehabilitation devices under real rehabilitation conditions [29].

In conclusion, VR was well tolerated by patients and should be considered an adjunct to conventional rehabilitation rather than a replacement for tools such as optokinetic stimulators and slaved environmental surrounds. Future research should focus on optimizing VR usage by enhancing the sense of embodiment and immersion, while also targeting more specific populations (e.g., patients with acute unilateral vestibular disorder) to assess whether VR could offer better outcomes in these groups.

## Supplementary Information

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Supplementary material 1.

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**Author contribution**
GL and CD conceptualized and designed the study. GL, GT, and SC were responsible for subject recruitment, conducting the intervention, and performing assessments. Data analysis and figure preparation were carried out by GL, CD, and FH. GL and GT took the lead in drafting the manuscript. IL provided supervision, critical review, and validation of the study. All authors have read and approved the final manuscript.

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**Data availability**
No datasets were generated or analysed during the current study.

## Declarations

**Ethics approval and consent to participate**
This study was approved by approved by the ethics committee *Sud-Est V* of Grenoble University Hospital Center (ID RCB: 2018-A02247-48), France.

**Consent for publication**
Not applicable.

**Competing interests**
The authors declare no competing interests.

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## Publisher's Note