Eye tracking by Virtual Reality Head Mounted Display provides biofeedback for gaze stabilisation exercises and enables on-the-fly measurement of Vestibulo-Ocular Reflex gain

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Research Article

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Eye tracking by Virtual Reality Head Mounted Display provides biofeedback for gaze stabilisation exercises and enables on-the-fly measurement of Vestibulo-Ocular Reflex gain

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Abstract:

Background: Vestibular hypofunction is a debilitating condition managed by vestibular rehabilitation protocol. Growing evidence indicates use of a virtual reality head mounted display (VR-HMD) based vestibular rehabilitation protocol improves adaptation responses by the vestibulo-ocular reflex (VOR), and reduction of symptoms. Currently such protocols only employ habituation exercises, and not gaze stabilisation.

Methods: A VR-HMD with integrated biofeedback system was designed to guide 8 participants (4 cases, 4 controls) through VR-based vestibular rehabilitation exercises, allowing the participants to self-correct for gaze stabilisation. VOR, angular VOR and patient discomfort were measured.
**Results:** Ipsilesional VOR of patients with unilateral vestibular hypofunction increased by 23.17% (SD: ±18.87%, p=0.01). One patient achieved a statistically significant decrease in aVOR for the contralesional side. Patient discomfort increased with the duration of the protocol.

**Conclusions:** This pilot VR-HMD protocol is a good alternative to classic gaze stabilisation exercises and allows for on the fly measurement of VOR. All patients with unilateral vestibular hypofunction demonstrated VOR gains. This is the first known study to employ biofeedback within the VR-HMD rehabilitation protocol that aids patients comply precisely to the exercises while also providing on-the-fly measurements for later examination and analysis. Further research is needed to optimise the technical considerations and tailor the rehabilitation protocol to patient needs and comfort.

**Keywords:** Vestibular Rehabilitation; Virtual Reality; Vestibular Hypofunction; Vestibulo-Ocular Reflex; Eye-tracking; Head Mounted Display

1. **Background**

Vestibular hypofunction is a common debilitating condition, prevalent among 6.7% of the general population, and may affect up to 95 million adults in Europe and the US alone [1]. Common symptoms include dizziness, sense of imbalance, nausea, sensitivity to motion, as well as ataxia and is usually exacerbated by head movements, hence impairing daily functioning and reducing the Quality of Life (QoL) of those affected [1]. Vestibular rehabilitation is an effective treatment for vestibular hypofunction and consists of exercises designed to provoke a vestibular response by introducing increasingly complex external stimuli in the form of movement exercises [2]. These exercises fall into two categories: (1) *habituation exercises* involving exposure to motion stimulus through a series of head movements without gaze fixation while (2) *gaze stability exercises* (GSEs) focusing either on repeated head movements while the patient’s gaze is fixated on an object, or following a moving object with their gaze, or a combination of both. In a number of studies, both habituation and gaze stability exercises have been proven to be equally effective in managing unilateral and bilateral vestibular hypofunction [3], though some studies have pointed to GSE being a superior intervention [4].
A number of emerging technologies have been used as an alternative to classic vestibular rehabilitation. Recent developments in high-immersion Virtual Reality Head Mounted Displays (VR-HMDs) commonly known as “Virtual Reality Goggles (VR Goggles)” or “Virtual Reality Headsets (VR Headsets)” allowed for the development of rehabilitation systems where VR exposure served as a stimulus responsible for the habituation effect. Similar to regular vestibular rehabilitation, interacting with VR through such devices improves short and long-term balance confidence and relieves symptoms of dizziness [5]. In recent meta-analysis, VR-based interventions were proven to be superior to betahistine treatment, dietary recommendations, as well as home exercises following Cawthorne-Cooksey protocol [5]. As of now, all protocols for rehabilitation using VR Goggles involve habituation exercises, and not gaze stabilisation.

Biofeedback methods enhance rehabilitation exercises by measuring biological data, such as Centre of Pressure and other parameters of body sway, and then relay this information back to the patient through visual or audio cues allowing for immediate self-correction [6]. Methods utilising biofeedback phenomenon were proven to be more effective compared to regular exercises for patients with vestibular hypofunction [7,8]. Although direct feedback from the physician is commonly utilised during classic gaze stabilisation exercises, no method for implementing biofeedback for gaze stabilisation exercises has yet been proposed.

Eye tracking functions in VR Goggles make it possible to combine the aforementioned phenomena. We developed a novel approach to vestibular rehabilitation which combines the habituation effect of VR with active gaze stabilisation exercises enhanced with a biofeedback effect by measuring gaze-ray information and head positioning data. Compliance with proper gaze stabilisation, speed and angles of head movement were relayed to the patient in the form of visual and audio cues.

To evaluate adaptation responses, we utilised eye tracking cameras that measured the vestibulo-ocular reflex (VOR). VOR is a phenomenon serving the same purpose in humans as head-bobbing in birds [9] - a reflex by which the human eye retains the fixation on objects during rapid head shifts by a series of contralateral opposing movements of the eye. It combines visual and vestibular
inputs and results in a synchronised movement of the oculomotor muscles. Under normal physiological conditions, the eye can compensate for head movement in its entirety, and remain fixed in relation to observed objects (VOR=1). However, during vestibular impairment, this compensation becomes less pronounced (VOR<1). As the VOR provides a quantifiable assessment of vestibular function [10] it can be used to assess the compensation mechanism after vestibular rehabilitation exercises [11].

The following study is the first reported use of a system utilising gaze stabilisation exercises using a VR-HMD, and is also the first to measure VOR gain during VR interaction as part of a vestibular rehabilitation scenario.

2. Methods

1. Setup

To study eye tracking, an HTC™ Vive™ Headset with the HTC™ Vive™ Binocular add-on (©Pupil Labs) was utilised with 20 light emitting diodes illuminating each eye, and two 200 Hz infrared, 192x192 resolution cameras, with 0.6-1° of gaze accuracy, 8.5 milliseconds of camera latency, and 0.08° precision. For unfiltered raw eye tracking data capture, we used Pupil Capture App (©Pupil Labs) [12].

Unity3D™ (©Unity Technologies, version 2018.3.10f1) was used to develop VR scenes. C# was used for plugins with Unity3D implementation being based on Open Source Pupil Reference plugin[13] (https://github.com/pupil-labs/hmd-eyes). VR user support, operator options editing, event handler, and positional data output plugins were implemented. Calibration for eye tracking was done with Pupil 2.8 (©Pupil Labs™). Content was displayed using the HTCTM Vive™ Headset equipped with two active-matrix organic light-emitting diode (AMOLED) screens, giving a combined resolution of 2880×1600 at 90 Hz refresh rate and with 110° field of view. A workstation running 64-bit Windows 10 with i7-7600U @3.90 GHz, Radeon RX 570 GPU, 16 GB of DDR3 RAM was used to run the software.
2. Participants

Four patients (median age 53.5±9.36, two women and two men) with unilateral vestibular hypofunction (UVH) were recruited to take part in the study. Patients were diagnosed by an otolaryngologist, based on physical examination demonstrating a positive head thrust test toward the ipsilesional side, and vestibular deficiency confirmed by videonystagmography. Patients were also screened for any cerebellopontine angle abnormalities using Computerised Tomography reports for head and neck; no abnormalities were found. Four age-matched controls (median age 49.5±10.5, one woman and three men) were also recruited, with no vestibular abnormalities and no current or past complaints of dizziness, vertigo, or gait disorders and with a normal Dizziness Handicap Inventory Score. All participants were examined by an ophthalmologist for visual acuity tests and autorefractor examinations to exclude those with vision defects above four diopters and for the purpose of modifying the VR-HMDs to utilise corrective lenses. In accordance with the Declaration of Helsinki the study was approved by the Bioethics Committee of Wroclaw Medical University as part of the grant UMW/S/0028626/19. Informed consent was obtained from all participants prior to the study.

Rehabilitation Protocol
Fig. 1 - Rehabilitation protocol. The protocol consists of 4 activities completed in order. VOR measurements are integrated into activity number 1 and number 4. 1.0 - Eye-tracking calibration; 1.1 - First horizontal gaze stability exercise and VOR measurement; 1.2 - Vertical gaze stability exercise; 1.3 - Gaze shift exercise; 1.4 - Second horizontal gaze stability exercise and VOR measurement

The rehabilitation software can be considered a VR implementation of rehabilitation devices already described in literature: an analog system by Migliaccio et al [14] and a subsequent digital system described by Mahfuz et al [15]. In these experiments, a red laser dot projected on a flat surface in a dim-lit or dark room served as a target to be observed by the study participants during vestibular rehabilitation.
exercises. Similarly in our case, a rendered mono-coloured disc in a VR space was placed 100 cm in front of the participants at a height matched to their eyesight [Fig 2.3].

The set of implemented exercises is adapted from Clinical Practice Guidelines for rehabilitation of vestibular hypofunction [16]. The training protocol consists of 4 exercises, each 5 minutes long, to be completed in order [Fig. 1] with around 150 repeated movements during each scenario. In our study, all scenarios took place in a rendered 3D space with neutral colouring and low polygon geometry consisting of one square room with a rendered area of an estimated 400m$^2$. Given the fact that the VR environment provided no point of reference for any participant-perceived motion other than the fixed point, 1m$^2$ grey and white tiles similar to patterns used for visual habituation in non-virtual vestibular rehabilitation exercises were used as floor texture to increase optical flow for scenes and to accentuate participant perceived motion [Fig 2.3].

All training scenarios were completed in a comfortable sitting position [Fig 2.1]. Study participants began the rehabilitation facing the calibration screen during which they briefly gazed at 5 calibration targets [Fig. 1.0]. After successful calibration, protocol started with horizontal gaze stability exercise [Fig. 1.1]. Participants were instructed to keep their gaze fixated on a single target, with their head kept straight in relation to the rendered horizon (neutral head position) [Fig 2.1]. Proper fixation on a target and head positioning were then confirmed, after which the target changed colour to green, indicating the beginning of the exercise. Participants were then instructed to quickly move their head horizontally from the neutral position outward while keeping their gaze on the target. The target disappeared after the peak head velocity was reached and reappeared after the participant returned their head into the neutral position, which signalled for another head movement similar to the previous described, but in the opposite direction. To assist the participants in properly following the instructions, visual (the target would briefly change colour to red) and audio (a high-pitch beep) cues were used to alert participants of any head movement below a peak velocity of 120° or for movements where their gaze did not remain on the target during lateral head shift.
The second exercise [Fig. 1.2] starts similar to the first exercise, with the head in the neutral position, but with each of the head movements done on an up-down axis. Visual and audio cues were again used to alert participants and to aid them in following the exercises properly.

The third exercise [Fig. 1.3] involved two alternating targets (labelled ‘a’ and ‘b’) 150 cm apart. The participant is instructed to make eye contact with the target ‘a’ after which the head is shifted from neutral position towards the same target. The target then disappears and target ‘b’ appears on the other side followed by eye rotation towards target ‘b’, then a head rotation towards the same target.

Third exercise [Fig. 1.4] is a repeat of exercise 1 [Fig. 1.1], during which angular VOR (aVOR) was measured.

Fig 2. - Study setup for Exercise 1. A participant in a comfortable sitting position (2.1) observes a 3D scene in Virtual Reality (2.3). Participant’s head position in space is measured to ensure it is kept straight relative to the virtual horizon. Gaze is measured by eye-tracking infrared cameras (2.2) to ensure that the participant is looking at the target (2.3)
3. VOR calculation

Raw data for pupil position and axis of gaze was exported from the eye tracking software at 200 Hz. Head positioning data as angles in relation to the 3D axes was exported through Unity plugin at 90 Hz synced to the gaze data and adjusted for system latency. Signals were then run through a 3rd order Butterworth filter with a cutoff-frequency of 0.04.

aVOR was measured during a lateral head thrust (Tab. 1, E1, E4) by dividing horizontal eye velocity ($\omega_{E}$) by horizontal head velocity ($\omega_{H}$). With $\theta_{H}$ being the angle of horizontal head rotation and $\theta_{E}$ the angle of horizontal eye rotation, aVOR = $\omega_{E}/\omega_{H} = \Delta \theta_{E}/\Delta \theta_{H}$. This was calculated for the 30 millisecond period before peak head velocity as aVOR estimates become unreliable for low head velocities. The onset of lateral head thrust manoeuvre and corresponding eye movement was defined by fitting $\omega_{H}(t)$ and $\omega_{E}(t)$ curves, and defined as time where $\omega_{H}$ and $\omega_{E}$ became greater than 2% of corresponding peak magnitudes of velocity. Impulses with peak magnitude below 150°/s and above 300°/s were not included in analysis.

Vestibulo-ocular reflex gain, quantifying the amount of compensation of aVOR, was calculated as a difference between pre-exposure aVOR to post exposure aVOR: $VG = \Delta aVOR$.

4. MISC scale

Severity of discomfort related to potential onset of Visually Induced Motion Sickness [VIMS] (ICD-10: T75.3 ICD-11: NF08.3) was evaluated through Misery Scale (MISC) Questionnaire [17]. MISC uses an 11 point scale signifying the intensity of symptoms related to VIMS, where a score between 1-5 described the intensity of symptoms preceding nausea, 6-10 described the intensity of nausea itself, and culminating in vomiting (10 on Misery Scale). To implement a self-reporting solution for MISC Questionnaire in VR we tied the score to clicks on the HTC VIVE controller buttons, with the slider displaying the current value to the participant through the headset, which was visible throughout the exercises. Responses were logged through the event handler plugin whenever the scale was adjusted. For the purpose of statistical analysis we prompted each participant to adjust the scale after each exercise was
completed, and exported the cumulative scores for each prompt (post exercise 1, post exercise 2, post exercise 3, post exercise 4)

5. Statistical analysis

Statistical analysis was done with StatSoft Statistica. Statistical significance was assumed at \( p<0.05 \). Two-way analysis of variance (ANOVA) tests were used for comparing pre-exposure to post-exposure aVOR gains, in relation to participant groups (patients with vestibular hypofunction versus controls) as well as the direction of movement (ipsilesional movement versus contralesional movement). For controls, affected sides (ipsilesional and contralesional) were randomly selected for the purpose of statistical analysis. Student t-test was used to evaluate the difference between pre- and post- aVOR gains for individuals. For MISC scores, total score, mean for groups, standard deviations and margin of error for 95% confidence interval were calculated. One way ANOVA and post-hoc Tukey Honestly Significant Difference (HSD) procedure was conducted afterwards to account for Type I errors due to multiple comparisons.

3. Results

1. VOR Gain

After the series of vestibular exercises, all patients with UVH improved on their ipsilesional (measurement during head impulse towards the affected) side [Tab. 1], with mean pre-exposure aVOR of 0.76±0.06 and mean post-exposure aVOR of 0.93±0.15 - an increase of 0.18±0.16 (23.17% ±18.87%), with the increase being statistically significant (p=0.01). For the contralateral side, average pre-adaptation aVOR was 1.04±0.08 compared to post adaptation 1.03±0.10 - a decrease of 0.017±0.13 (-1.67%±13.13%) which was not statistically significant (p=0.29).

In controls, the ipsilesional vs contralesional side was selected at random and was not tied to the VOR values during initial testing. For the ‘ipsilesional’ side mean aVOR pre-exposure was 1.03±0.05, while post-exposure was 1.13±0.03 which constituted a 0.10±0.11 increase (10.01%±10.29%). For the
'contralesional' side, mean aVOR pre-exposure was 1.01±0.06, post-exposure: 1.10±0.03 which constituted a 0.09±0.11 increase (8.35%±10.20%). For the control group, increases for both 'ipsilesional' and 'contralesional' sides were not significant (p=0.08).

Across all individual scores, only one patient achieved a statistically significant (p=0.03) decrease in aVOR for the contralesional side with a 0.14±0.072 decrease (-11.86%±6.38%). All other decreases were not found to be statistically significant.

aVOR gain for patients and controls is presented in [Fig. 3] with the results for aVOR parameters for all participants presented in [Tab. 1]

<table>
<thead>
<tr>
<th>diagnosis</th>
<th>Ipsilesional (adapting) side</th>
<th>Contralesional (non-adapting) side</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aVOR pre</td>
<td>SD</td>
</tr>
<tr>
<td>ULVH</td>
<td>0.69 ± 0.10</td>
<td>0.90* ± 0.07</td>
</tr>
<tr>
<td>ULVH</td>
<td>0.72 ± 0.06</td>
<td>0.81* ± 0.15</td>
</tr>
<tr>
<td>ULVH</td>
<td>0.83 ± 0.04</td>
<td>1.16* ± 0.06</td>
</tr>
<tr>
<td>ULVH</td>
<td>0.78 ± 0.05</td>
<td>0.85* ± 0.08</td>
</tr>
<tr>
<td>control</td>
<td>1.08 ± 0.03</td>
<td>1.09 ± 0.04</td>
</tr>
<tr>
<td>control</td>
<td>1.04 ± 0.08</td>
<td>1.03 ± 0.11</td>
</tr>
<tr>
<td>control</td>
<td>0.96 ± 0.13</td>
<td>1.27* ± 0.07</td>
</tr>
<tr>
<td>control</td>
<td>1.02 ± 0.03</td>
<td>1.12 ± 0.10</td>
</tr>
</tbody>
</table>

**Tab. 1 - results for aVOR for pre-exercise and post-exercise testing. UVH - unilateral vestibular hypofunction. Individual differences between pre- and post-exercise in aVOR gain with statistical significance (p<0.05) underscored and marked with *"
Fig 3. - aVOR scores for ipsilesional (A) and contralesional (B) sides. Gain between the pre-exercise and post-exercise represented by full lines for patients and dotted lines for controls.

Fig 4. - Exemplary results for aVOR gain in unilateral vestibular hypofunction patient: Angular velocity in degrees/second plotted for time counted from the onset of thrust. A - pre-exercise B - post-exercise. Head movement is represented by dotted curves, eye movement by full curves. Head manoeuvre curves inverted to match eye thrust curves.

2. MISC scale

MISC scores during rehabilitation increased with exposure, with none of the participants reporting scores higher than 4. No nausea was reported during any of the exercises. Highest scores were reported
post exercise 4 (E4). Due to the small number of participants and negligible differences between mean MISC scores of patients and controls, ANOVA was run for combined MISC scores (f-ratio=6.73715, p=0.000394). In Tukey's HSD MISC scores post exercise 3 (E3) to post calibration (HSD=1.63, Q=4.84, p=0.01308); post exercise 4 (E4) to post calibration (HSD=2.13, Q=6.32, p=0.00071) and post exercise 4 (E4) to post exercise 1 (E1) (Q=5.21, p=0.00652) proved statistically significant [Fig. 5 - marked with *].

![Graph](image)

**Fig 5.** Mean Misery scale (MISC) scores ± SE (A) and combined scores (B) for controls and patients. Dashed line represents controls, solid line represents patients with unilateral vestibular hypofunction. Scores were measured during exposure at 2, 7, 12, 17 and 22 minutes (corresponding to post calibration (Cal), post exercise 1 (E1), post exercise 2 (E2), post exercise 3 (E3), post exercise 4 (E4)).

### 4. Discussion

Modern VR-HMDs are uniquely equipped to serve as a base as personalised vestibular rehabilitation tools. Rehabilitation systems utilising interaction with 3D space through augmented reality [18], immersive projection theatres [19,20], and VR-HMDs using exposure to motion [21,22], or gaming tasks [23,24] have already been proven to help in recovery from vertigo and imbalance, increasing overall stability and gait [5]. Currently available consumer grade VR devices shift from being an accessory requiring a computer with dedicated room-wide tracking systems to all-in-one units that can be used
independently from other devices, with minimal setup (such as Oculus Quest 2™, Vive Focus 2™) and some equipped with eye tracking hardware (Pico Neo 2™, Playstation VR2™). As the technology improves, creation of new rehabilitation tools will be made easier, as will the potential availability for the patients.

Although eye-tracking solutions were not previously present in most consumer grade VR helmets, their potential benefits for the gaming industry such as foveated rendering [25] may change this to make eye tracking user interfaces [26] more prevalent in consumer grade electronics.

The benefits of eye-tracking hardware for vestibular rehabilitation is two-fold: firstly, eye-tracking enables incorporating biofeedback into gaze exercises, which have been proven to not only increase long-term but also immediately improve postural stability [27]. Gait rehabilitation systems for neurological disorders [28] also use the phenomenon of biofeedback with strong evidence indicating positive effects on dynamic balance and gait for neurological patients [29]. Biofeedback for tracking head movements has already been a staple of gaze rehabilitation systems. In studies by Migliaccio et al and Mahfuz et al, visual and audio cues from the system informed the user on proper speed or angle for the head rotation. We used a similar approach in our study for head movement, with the additional benefit of being able to convey information about gaze stability as well, as our simulated target was programmed to change colour when the gaze of the patient was not detected. Moreover, the specific use of eye-tracking based biofeedback in VR was tested by Park et al [30] which showed saccadic exercises to be more accurate with visual biofeedback provided by eye-tracking, compared to exercises without biofeedback.

Secondly, eye-tracking allows the calculation of VOR for the purpose of estimating the intervention effect. Gain in VOR has been proven to be a reliable parameter that can be used to quantify the rehabilitative effect of gaze stabilisation exercises [10] and can be correlated to reduction in dizziness, oscillopsia and improved dynamic visual acuity [31].

To measure VOR, rehabilitation systems like Migliaccio et al [32] utilised magnetic field and magnetic search coils embedded within contact lenses. This system, further described by [33], has the
benefit of easily allowing for high fidelity, high frame-rate (500Hz) signals that can be combined with a synchronised measurement of head position using another coil attached to the patient’s head. As digital camera technology improved, studies like Migliaccio et al [14] started utilising a system described previously by MacDougall [34], with high-frame rate digital cameras aimed at mirrors reflecting corneas. Our system operates on a similar principle, albeit with a lower framerate. VOR calculation in VR helmets through eye-tracking cameras has already been implemented once for the purpose of depth estimation - Mardanbegi et al [35] used a consumer grade VR helmet with integrated eye-tracking (HTC VIVE, Tobii Technologies) to successfully calculate VOR during head shifts. During our preliminary data collection and test-kit assembly, we found the angles commonly provided by eye tracking cameras to be suboptimal for VOR evaluation, but this was remedied by fine tuning the camera placement and shifting it to achieve a more obtuse angle. A more direct approach, using MacDougall’s [34] original mirror idea was also considered at some point, but was abandoned as the test kit assembled with mirrors often shifted during rapid head movements, introducing measurement bias, as well as difficulties with adjusting eye tracking software.

Although some studies had suggested that current eye-tracking solutions were not viable for assessment in ophthalmological evaluation [36], the quality of our eye-tracking data was in line with other studies evaluating consumer grade VR systems [37]. As expected from an optical eye-tracking system, noise in the software-calculated gaze-ray data stream was an issue, and may have lowered the quality of measurements taken. As a potential solution to that problem, Mardanbegi [35] suggested using post-hoc analysis of direct video feed from eye tracking cameras instead of relying on eye-tracking data (gaze-ray velocity) calculated by eye tracking software. This solution for aVOR gain calculation was not attempted because this study was planned as a first step for creating a tool for personalised vestibular rehabilitation; for that purpose ad-hoc aVOR gain measurements were prioritised to allow for on-the-fly algorithm adjustments in the future. A sampling rate of 200 Hz for eye tracking measurements was enough to reliably calculate aVOR vestibular testing, with other studies utilising optical systems being able to reliably calculate angular velocities at as low as 50 Hz, with higher sampling rates being more reliable for
calculating peak velocities for shorter eye saccades [38]. As both quality and cost effectiveness of high speed eye tracking cameras dramatically improved in the last decade, further evaluation is needed for both angular velocity estimates derived from eye-tracking in a clinical setting.

The utilisation of VR in the rehabilitation exercises is not without its issues. Similarly to other studies utilising VR in vestibular rehabilitation, patient discomfort increased as the exposure to VR continued, with MISC scores continuously rising alongside the exposure. In the future we plan to manage this issue by introducing longer breaks during the VOR adaptation protocol since breaks increase retention time, [39] with VOR gains persisting for over one hour.

The rehabilitation protocol utilised was limited in scope - with only x1 VOR exercises being implemented. Other studies suggested that incremental VOR adaptation exercises were proven to be more effective in improving gait and improving Dizziness Handicap Inventory scores [40]. Vergence effects on VOR [32] could also potentially be used to increase the rehabilitative effect by programming the simulated point to be closer to the patient. We plan to test the effectiveness of such rehabilitation scenarios in a further study. Similarly, a more sophisticated rehabilitation protocol could manipulate the VR environment (“scene content”) to provide habituation effects, as previous studies have proven that exposure to habituation exercises in a virtual environment is similarly effective in outcomes to physical therapy [41]. Our setup utilising VR with eye tracking provides us with freedom to test such scenarios in a controlled environment with complete control over visual stimuli.

5. Conclusions

The VR system utilised in this study proved to be a good alternative to classic gaze stabilisation exercises. All patients with unilateral vestibular hypofunction increased in active VOR gains by an average of 23.17% on their affected side. The calculation of VOR through eye tracking cameras in VR-HMDs is possible for the purpose of medical rehabilitation, but due to suboptimal technical factors, further research and testing is necessary. This study was intended as a pilot study to set-up and create the VR based vestibular rehabilitation protocol and VR program to observe preliminary results and detect potential issues in a
small group of participants. Prolonged gaze stability exercises in VR may lead to patient discomfort, hence for the purposes of prolonged use, or at-home use with no physician supervision, there is a need to develop integrated systems to measure patient discomfort. This is the first known study to employ biofeedback within the VR-HMD rehabilitation protocol that aids patients comply precisely to the exercises while also providing on-the-fly measurements for later examination and analysis. The proposed VR system will allow for creation of a compact personalised tool that will adapt the exercises based on measured VOR gain and tailor the rehabilitation protocol. Further research regarding implementation of other forms of VOR training such as incremental VOR gain exercises, scene content modification and habituation exercises is needed.

6. Acknowledgements

The study was funded as part of the project “Virtual Reality system for computer guided Vestibular Rehabilitation” and funded by Wroclaw Medical University grant UMW/S/0028626/19.

List of abbreviations

QoL: Quality of Life

VR: Virtual Reality

HMDs: Head Mounted Displays

VOR: Vestibulo-Ocular Reflex

aVOR: Angular Vestibulo-Ocular Reflex

UVH: Unilateral Vestibular Hypofunction

Declarations:

Ethics approval and consent to participate: This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving patients were approved by the Bioethics
Committee of Wroclaw Medical University as part of the grant UMW/S/0028626/19. Informed written consent was obtained from all participants prior to the study.

Consent for publication: Not applicable

Availability of data and materials: All data generated or analysed during this study are included in this published article and further data may be available on request to the corresponding author.

Competing interests: The authors declare that they have no competing interests

Funding: The study was funded as part of the project “Virtual Reality system for computer guided Vestibular Rehabilitation” and funded by Wroclaw Medical University grant UMW/S/0028626/19.

Authors’ contributions: J.N. and T.Z. recruited patients, conducted the study and procured the equipment required for the study. J.N. performed the data analysis, interpreted the data, and led the writing of the manuscript with N.M. N.M. and T.Z. contributed in reviewing and editing the manuscript. All authors read, reviewed, and approved the final manuscript.

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