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Original Research Article

Subjective visual vertical assessment with mobile virtual reality system

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ABSTRACT

Background and objective: The subjective visual vertical (SVV) is a measure of a subject's perceived verticality, and a sensitive test of vestibular dysfunction. Despite this, and consequent upon technical and logistical limitations, SVV has not entered mainstream clinical practice. The aim of the study was to develop a mobile virtual reality based system for SVV test, evaluate the suitability of different controllers and assess the system's usability in practical settings.

Materials and methods: In this study, we describe a novel virtual reality based system that has been developed to test SVV using integrated software and hardware, and report normative values across healthy population. Participants wore a mobile virtual reality headset in order to observe a 3D stimulus presented across separate conditions – static, dynamic and an immersive real-world (“boat in the sea”) SVV tests. The virtual reality environment was controlled by the tester using a Bluetooth connected controllers. Participants controlled the movement of a vertical arrow using either a gesture control armband or a general-purpose gamepad, to indicate perceived verticality. We wanted to compare 2 different methods for object control in the system, determine normal values and compare them with literature data, to evaluate the developed system with the help of the system usability scale questionnaire and evaluate possible virtually induced dizziness with the help of subjective visual analog scale.

Results: There were no statistically significant differences in SVV values during static, dynamic and virtual reality stimulus conditions, obtained using the two different controllers and the results are compared to those previously reported in the literature using alternative methodologies. The SUS scores for the system were high, with a median of 82.5 for the Myo controller and of 95.0 for the Gamepad controller, representing a statistically significant difference between the two controllers ($P < 0.01$). The median of virtual reality-induced dizziness for both devices was 0.7.

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Conclusions: The mobile virtual reality based system for implementation of subjective visual vertical test, is accurate and applicable in the clinical environment. The gamepad-based virtual object control method was preferred by the users. The tests were well tolerated with low dizziness scores in the majority of patients.

1. Introduction

The subjective visual vertical (SVV) refers to an individual's ability to indicate what he or she perceives to be an Earth vertical line, in the absence of an external reference frame. A tilt of the SVV is a sensitive sign of a vestibular tone imbalance, resulting from lesions affecting central and peripheral vestibular pathways. Peripheral pathways run from the vestibular apparatus (semicircular canals and otolith organs) to the vestibular nuclei, via the vestibular nerve, and central pathways from the vestibular nuclei via the medial longitudinal fasciculus (MLF) and interstitial nucleus of Cajal (INC) to a widespread cortical vestibular network [1]. SVV tilts are therefore observed across a range of vestibulopathies. Indeed, abnormal SVV has been reported in over 90% of patients with acute unilateral brainstem lesions affecting central pathways involved in gravitational perception [2]. SVV tilts are thought to arise as part of the ocular tilt reaction (OTR) characterized by the additional features of head tilt, ocular torsion, and skew deviation [3]. In support of this hypothesis, a tight correlation between torsional eye position and the SVV tilt has been described [4]. Unilateral brainstem lesions caudal to the pons lead to ipsiversive OTR and SVV tilts, whereas more rostral lesions involving the MLF or INC typically cause contraversive OTR and SVV tilt [2,5].

SVV is usually tested in a ''static'' condition, where subjects are asked to align a rod or line to Earth vertical against a black stationary background, devoid of reference frames. Recent studies demonstrate additional benefits of dynamic SVV test, whereby the rod or line is presented against a moving background (typically consisting of ''dots'' or ''spheres'') [6–8]. Dynamic conditions increase the sensitivity of the test, in addition to quantifying the degree of visual dependency – an over-reliance on vision for balance where other sensory modalities may be more appropriate [9]. Despite its clinical value in the diagnosis, topographical localization, and identification of impaired graviceptive (otolithic and vertical semicircular canal) function, the SVV has not entered mainstream clinical practice. This is mostly because SVV has been traditionally measured using specialist equipment involving the computerized ''hemispheric dome'' method, or a computerized ''light-bar in the dark'' method [8,10]. More recently, the ''bucket test'' was introduced as an inexpensive, easy-to-make, and easy to apply and operate method of testing the SVV at the bedside [11,12]. Although it has yielded reliable results, such a method is not without its limitations; namely a low resolution, and the ability to perform only static SVV tests [11,12]. Additional software-based, flexible multi-function systems have been proposed, but these systems are PC- or laptop-based and are less readily portable than hand-held devices [13].

In this study, we describe a virtual reality (VR) based system (VIRVEST) that has been developed to test SVV, and report normative values across healthy population. We sought to compare SVV results using VIRVEST system with previously reported in the literature using alternative methodologies. Additionally we wanted to choose controller which would be accurate and at the same time easy to use for the participants. Therefore, we selected 2 possible control devices and compared the differences between them. As it is known that virtual reality itself can cause dizziness, we wanted to evaluate possible virtually induced dizziness.

2. Materials and methods

2.1. *VIRVEST system*

VIRVEST is a wearable VR-based system that enables the physician or technician (herewith termed ''tester'') to acquire SVV data from a subject or patient (herewith termed ''participant''). The equipment is integrated by using the proposed software and hardware applications shown in Fig. 1. The participant wears a mobile virtual reality application (Mobile Application for Virtual Reality) in order to observe a 3D stimulus presented across four separate conditions. The virtual reality environment is controlled by the patient using a Bluetooth connected controller. In this study, we used the Samsung Galaxy S7 smartphone and Samsung Gear VR headset for virtual reality scene presentation. Participants controlled the movement of an ''arrow'' (Tests 1–3), or ''boat'' (Test 4) using either a Myo gesture control armband (Thalmic Labs Inc., Canada) or a general purpose gamepad (Red Samurai gamepad, GameStop Corp. Inc., US). The Myo armband (Fig. 1) was worn over the participant's forearm, and enabled the participant to rotate the arrow or boat wirelessly using pronation and supination arm motions. The Myo device consists of a set of electromyographic sensors, combined with a gyroscope, accelerometer and magnetometer to recognize arm gestures. The gamepad consisted of two buttons, left and right, which participants were asked to press to adjust the arrow or boat to their perceived vertical.

A second mobile device and software application (see mobile application in Fig. 1) was used to control the delivery of the VR stimulus. Additionally, this application allows the tester to visualize the test results both online and offline. The two mobile applications use Bluetooth connection in order to exchange the commands and data. The mobile application of the tester allows the data to be saved to a local database or to

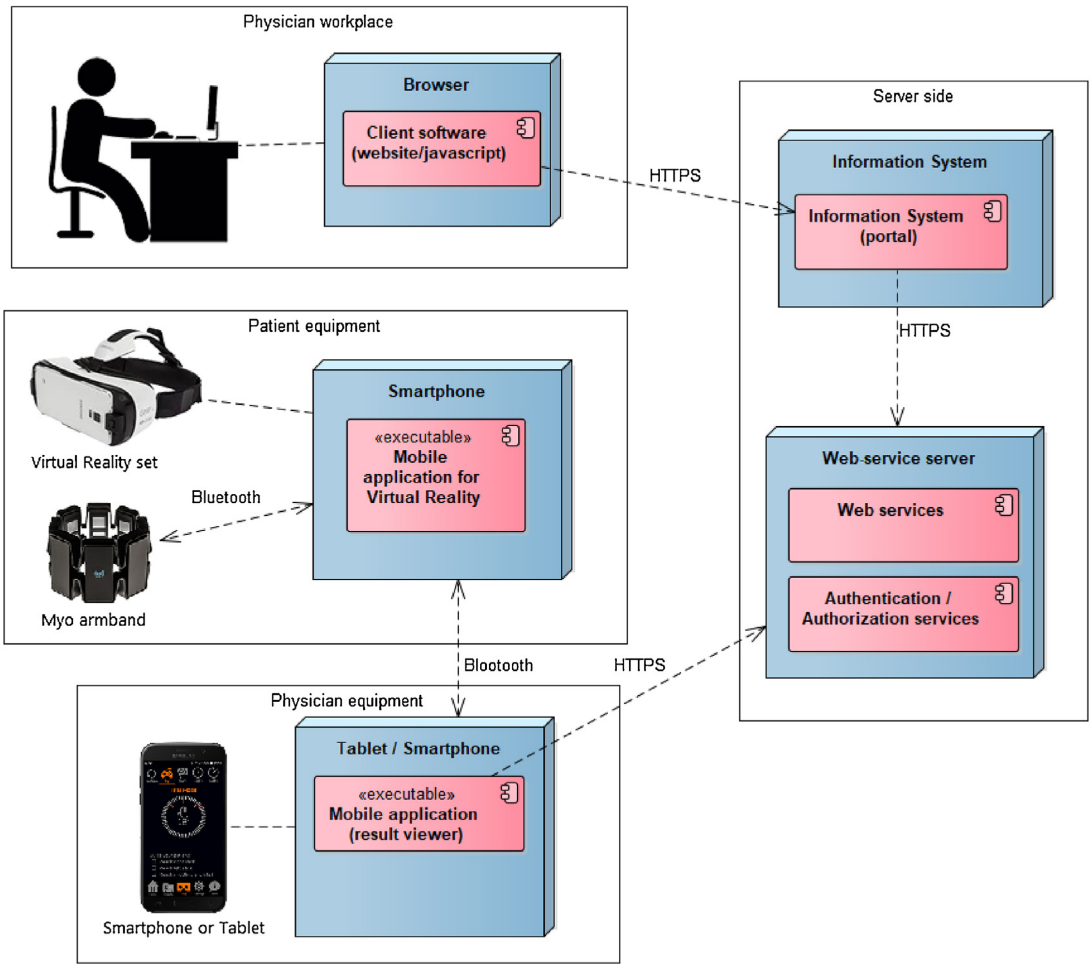


Fig. 1 – The component diagram of the proposed software system VIRVEST for assessment of subjective visual vertical.

be sent to the web server. In order to send the data to the web server, an Internet connection must be available. Authentication and authorization is performed using OAuth 2 protocol while the security of the transferred data is guaranteed by using https protocol. The received data is stored in the information system. The website incorporates a responsive web design in order to provide adapted view for different devices.

2.2. *Participants*

A total of 41 healthy young adult volunteers participated in this study: 14 men (age 28.14 ± 0.6 years) and 27 women (age 27.52 ± 0.5 years). All participants signed an informed consent and the study was approved by Kaunas Regional Biomedical Research Ethics Committee (NR-BEC-LSMU(R) 06). Participants had no complaints of dizziness or vertigo during the last 6 months. A full neuro-otological assessment comprising videonystagmography and cervical vestibular myogenic evoked potentials were performed for all participants and revealed no pathological changes.

This study was approved by the appropriate ethics committee and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. All subjects gave their informed consent prior to their inclusion in the study.

2.3. *SVV tests using the VIRVEST system*

Prior to starting the SVV acquisition, a calibration of the controller device was performed and the participants asked to adjust the focus on the VR headset. Four tests were performed: static SVV (Test 1), dynamic SVV with clockwise background stimulus rotation (Test 2), dynamic SVV with counter-clockwise background stimulus rotation (Test 3), and SVV with a virtual reality background (Test 4). The screenshots for all tests are shown in Fig. 2A–C. Six trials were performed for each test. For all tests and trials, participants using the Myo armband were asked to manipulate the arrow (or boat) using the controller and to verbally indicate when they had reached their perceived vertical. The tester then activated the next trial (or condition) from his/her mobile device. When using the gamepad, participants were instructed to press one button to orient the arrow (or boat) to their perceived vertical, and the second button to confirm they had reached the perceived vertical. The second press of this button activated the subsequent trial (or test).

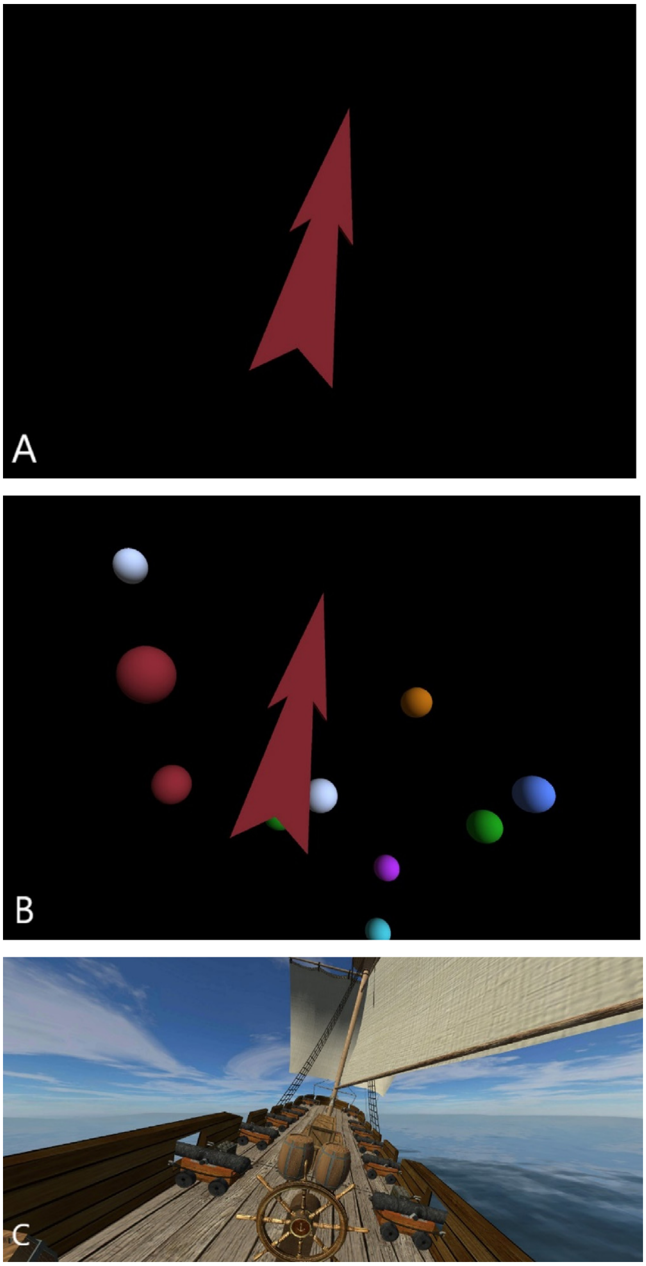


Fig. 2 – The view of virtual reality application: (A) static SVV test, (B) dynamic SVV test, (C) "realistic" SVV test. During static and dynamic SVV tests, the patient is asked to align the object vertically, the same holds for "realistic SVV" test – the patient is asked to align the boat vertically.

In the static test the visual stimulus consists of a block arrow over a black background (Fig. 2A). The subject is instructed to align the tip of the arrow to the perceived Earth vertical ("ceiling to floor"). An arrow shape was chosen to avoid any 90° angles and thus avoid presenting additional right-angled frames of reference that may bias the perception of verticality and thus the SVV data. At the beginning of the test, the stimulus is presented with an initial random inclination of 10–15°.

For the dynamic test, the black background includes colored spheres (to increase the salience of the background stimulus [8]) rotating in either clockwise or counter-clockwise directions (Fig. 2B). Predetermined parameters for the dynamic SVV were selected for this study, but can be modified on the tester's mobile application. Thus, the number of spheres in the background screen was set to ten. Based on pilot data, the background motion was set to a constant velocity of 10°/s given that higher values tended to interfere with accurate verticality perception in healthy controls. The software program does allow for variable velocities of the spheres, each sphere moving at a randomized different velocity between 5°/s and 15°/s. Dynamic SVV tests include clockwise and counter-clockwise background motion rotation as handedness is known to exert different effects on SVV according to the direction of the background motion.

The "realistic" SVV refers to a dynamic, immersive real-world stimulus, consisting of a boat sailing in an open sea, with the subject perceiving to stand directly in front of the boat's mast (Fig. 2C). In the beginning of the test, the central stimulus (the boat) is presented at a random inclination of 10–15°. Participants were instructed to align the boat to the Earth vertical, with no specific instruction as to whether they should focus on the mast. In order to ensure that the horizon did not present a reference point, horizon was set to naturally oscillate where it intersected with sea waves. Furthermore, the boat was set to sway in the pitch plane (in addition to its roll incline) as it ascends and descends each wave, thus obscuring the horizon. The boat sway was set using a sinusoidal function with declinations from 7.5° to 7.5° at a frequency of 0.1 Hz while horizon waves expose random behavior. Additional stimuli such as heavy clouds, raining, and fog can be switched on in order to further distort evidence of verticality but were not utilized in the current study.

We report normative values across a healthy population and compare our SVV results using the VIRVEST system to previously published SVV values that have used alternative computerized methodologies [10,13]. We also sought to evaluate differences in SVV tilt in healthy controls comparing the use of the Myo armband and a general purpose gamepad to control the arrow (or boat).

Moreover, we wanted to evaluate the developed system with the help of system usability scale questionnaire and to evaluate possible virtually induced dizziness with the help of subjective visual analog scale.

2.4. *System usability scale (SUS)*

To assess the usability of the VIRVEST, a measure of the ease of use for learning and handling, we employed the system usability scale (SUS), a global, widely employed, subjective assessment of usability [14]. The scale is an effective, reliable tool for measuring the usability of a wide variety of products and services, including Web sites and applications, cell phones, interactive voice response systems, and TV applications [15]. The SUS is composed of 10 statements, each having a 5-point Likert-style scale that ranges from 1 (strongly disagree) to 5 (strongly agree), with five positive statements and five negative statements, that alternate [14]. Scoring is accomplished by subtracting 1 from odd-numbered (positively worded) responses and subtracting the even-numbered negatively worded responses from 5. The sum of scores is then multiplied by 2.5 to obtain a score between 0 and 100. A total of 68 points represent the average usability score across systems [15]. The total scores also correspond with seven qualitative adjective ratings, ranging from "worst imaginable" at the low end to "best imaginable" at the high end or range 0–64 (not acceptable), 65–84 (acceptable), and 85–100 (excellent) [15,16]. The linguistically and culturally adapted Lithuanian version of the SUS was utilized in this study. All participants were asked to evaluate separately the usability of the VIRVEST system after using each of two control modalities, i.e. SUS Myo and SUS Gamepad immediately after performing the SVV tests. A cross-over design was used such that participants using the Myo armband were asked to repeat all conditions using the Gamepad, within a 24-h period. The order (Myo first versus Gamepad first) was randomized across participants. Participant evaluations were completed after completing each paradigm.

2.5. *Virtual reality induced dizziness*

Additionally we assessed for possible virtual reality-induced dizziness (VRID) using a subjective visual analog scale (VAS). Subjects were asked to evaluate their VRID on a 10-cm long VAS from 0 indicating no dizziness at all to 10 indicating severe dizziness.

2.6. *Statistical analysis*

The mean value of the six measurements for each condition was used for the data analysis, which was performed with SPSS 22 for Windows. Shapiro–Wilk test variables of SVV with normal distribution were analyzed with paired Student t test and variables which did not present normal distribution were analyzed with Wilcoxon Signed Ranked Test. In all tests, the criterion for statistical significance was $P < 0.05$.

3. Results

3.1. *SVV tilts*

The results for the SVV values for both the Myo armband and Gamepad controllers are presented in Table 1. We found no significant differences between the distribution of positive and negative values of SVV deviations therefore only positive values were used in the analysis. There were no statistically significant differences in SVV values obtained using the two different controllers.

3.2. *System usability scale*

In the present study, the SUS scores indicated the degree to which the VIRVEST design was appropriate and easy to use from the participant's point of view. As shown in Table 2, the SUS scores for the VIRVEST system were high, with a median of 82.5 for the Myo controller and of 95.0 for the Gamepad controller, representing a statistically significant difference between the two controllers ($P < 0.01$).

3.3. *VRID results*

VRID was evaluated by means of the VAS and the results are summarized in Figs. 3 and 4, showing that several participants experienced some degree of dizziness, with the vast majority experiencing only very mild dizziness. Overall results show that the VIRVEST system tests did not cause dizziness in the majority of participants.

4. Discussion

We have developed a VR system for SVV evaluation. This system has the advantage of being fully portable, comfortable, able to test SVV across static and dynamic conditions, with a high angular resolution, and able to capture temporal and spatial characteristics of the SVV behavior within trials.

Despite large variations in SVV paradigms across studies, in conditions of darkness and in an upright trunk posture, normal SVV values (mean of SVV estimates) range from -2.5° to 2.5° [2]. Thus, a difference ≥2° between repeated measures for a given patient can be interpreted as a real change in SVV perception [17]. Our healthy participant SVV data using the VIRVEST system are comparable with normative values reported in the literature. For example, in Pavan et al. healthy static SVV reported values were $0.37 \pm 1.21^\circ$, dynamic SVV

Table 1 – SVV results for two object control methods in VIRVEST system.

Test type	Values obtained with Myo ($n = 41$)	Values obtained with Gamepad ($n = 41$)	P
Static SVV,°	1.25 (0.68) [1.02–1.47]	1.13 (0.77) [0.87–1.38]	0.3[a]
Dynamic clockwise SVV,°	2.34 (1.07) [1.98–2.69]	1.94 (1.3) [1.51–2.37]	0.07[b]
Dynamic counter clockwise SVV,°	1.31 (0.8) [1.05–1.58]	1.25 (0.79) [0.99–1.51]	0.57[b]
Virtual reality stimulus (boat on the water),°	1.12 (0.8) [0.85–1.39]	1.05 (0.8) [0.79–1.32]	0.68[a]

Values are mean (standard deviation) [95% confidence interval].
[a] Wilcoxon signed ranked test.
[b] Paired Student *t* test.

Table 2 – Results of the SUS evaluation ($n = 41$).

Control modality	Median	Minimum	Maximum	Interquartile range
Myo	82.5	15	100	22.50
Gamepad	95.0	55	100	12.50

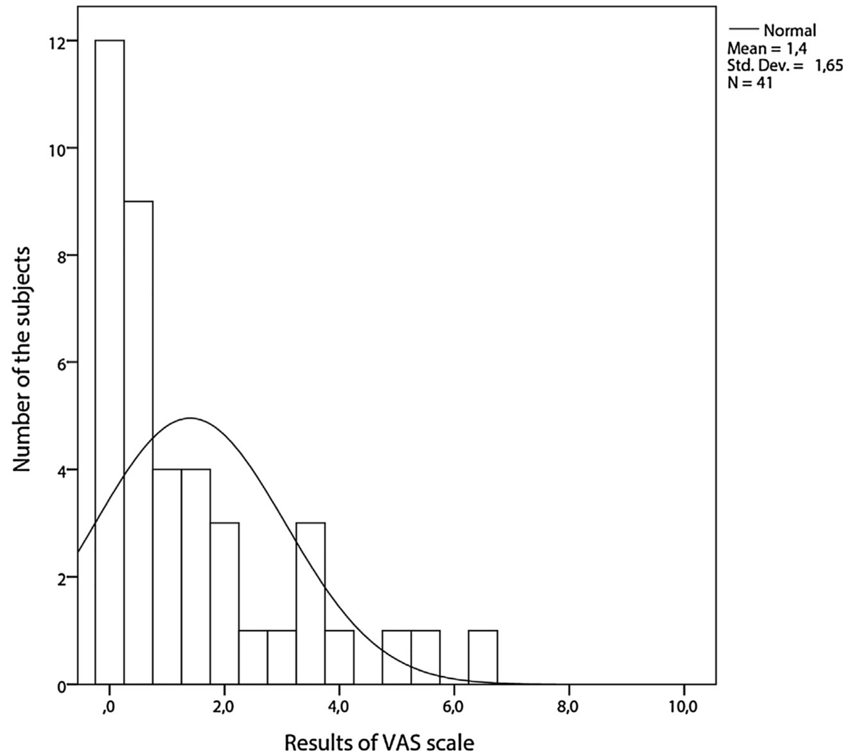


Fig. 3 – Results of VAS evaluation after testing with Myo ($n = 41$).

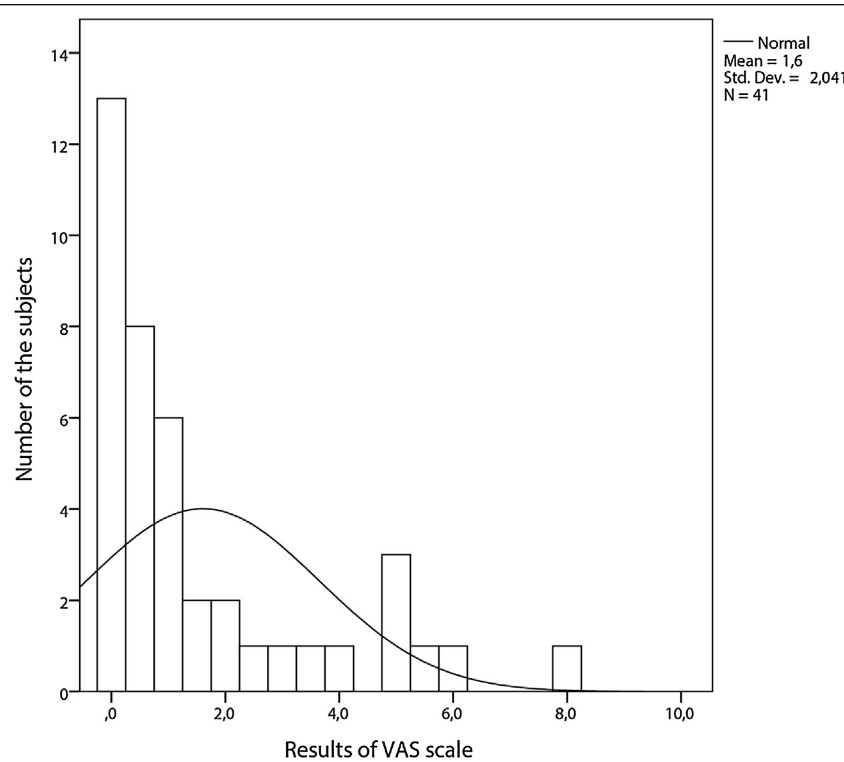
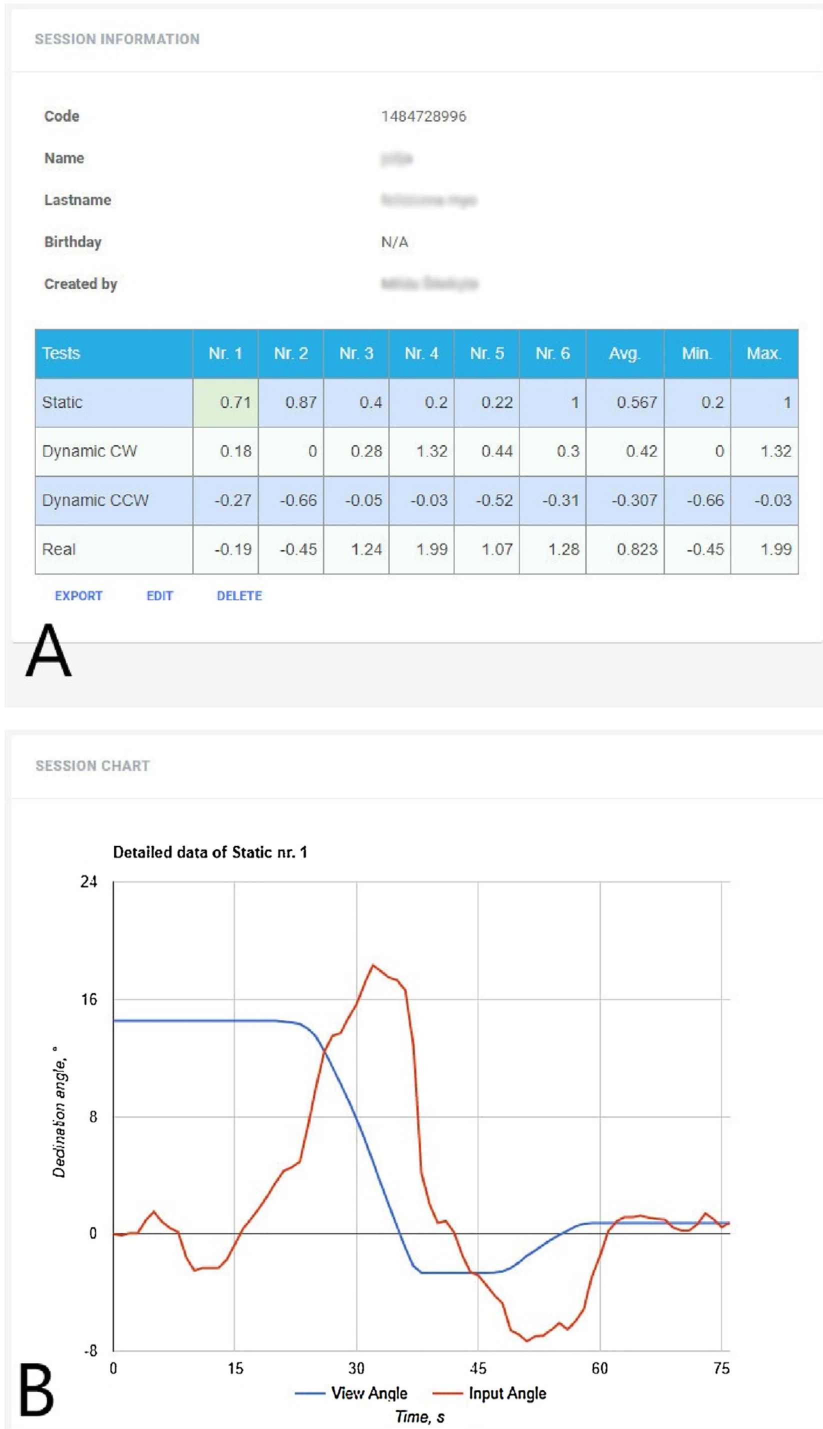


Fig. 4 – Results of VAS evaluation with Gamepad ($n = 41$).

(clockwise) $1.53 \pm 1.8°$, and dynamic SVV (counter clockwise) $1.11 \pm 2.46°$ [13]. Similarly, in an Indian healthy population, Ashish et al. reported static SVV values of $1.52 \pm 0.70°$, dynamic SVV (clockwise) of $1.96 \pm 0.65°$, and dynamic SVV (counter clockwise) of $1.96 \pm 0.65°$ (see Table 1 for comparison) [10]. The virtual reality stimulus (boat on the water) SVV tilts were comparable to those of the static SVV, despite the 'dynamic' nature of the scene. This is not unexpected, as the background scene did not rotate uniformly or unidirectionally, as is the case for the dynamic SVV with the moving spheres. Studies assessing the perceived upright of a variety of scenes have shown that SVV tilts are affected by the nature of the scenes being viewed. Thus, man-made scenes (such as the inside of a room) tend to cause lesser SVV tilts than natural scenes (such as a park) perhaps related to a greater number of vertical lines present in man-made scenes compared to natural scenes, thus offering greater orientation cues [18]. Therefore, VIRVEST offers the possibility to introduce different



Tests	Nr. 1	Nr. 2	Nr. 3	Nr. 4	Nr. 5	Nr. 6	Avg.	Min.	Max.
Static	0.71	0.87	0.4	0.2	0.22	1	0.567	0.2	1
Dynamic CW	0.18	0	0.28	1.32	0.44	0.3	0.42	0	1.32
Dynamic CCW	-0.27	-0.66	-0.05	-0.03	-0.52	-0.31	-0.307	-0.66	-0.03
Real	-0.19	-0.45	1.24	1.99	1.07	1.28	0.823	-0.45	1.99

Fig. 5 – Session view in a website: (A) representative tabulated outcome data showing obtained results of each test, performed 6 times and the estimated average, (B) the angle of the vertical over time (blue curve) and rotation of the controller over time (red line). The arrow starts with a rotation angle of 16° clockwise (0–20 s). The patient rapidly rotates the arrow using the Myo device to an approximate vertical position (20–35 s). Following this, the patient makes smaller adjustments to achieve a more precise perceived vertical position (35–60 s). The participant required only two rotations to complete the trial. The behavioral waveform suggests that the participant was certain about their verticality perception.

scenes that can be tested across different populations, to explore man-made scenes versus natural scenes further. Moreover, ''reality'' stimuli may be useful for testing the pediatric population as it provides a more ''everyday'' life environment.

It is increasingly recognized that SVV should be performed not only in static conditions but also incorporate dynamic conditions to increase the sensitivity of the test [7,8,10,13]. A full-field roll-plane rotation of the visual scene induces a sensation of apparent self-motion, therefore the dynamic visual vertical induces a greater tilt of the perceived visual vertical than the static condition [19]. This is most marked in patients with increased ''visual dependency'', for example in labyrinthine deficient patients [20]. It is however worth noting that there exists great variability in dynamic SVV values within a healthy population, with tilts ranging from 0.49° to almost 11° between studies [7,10,13]. Whilst such variability could be due to different dynamic stimuli, age of the subjects, and study size, one wonders whether this may also represent variation in visual dependency within the healthy population. Indeed, patients with migraine often report symptoms of increased visual dependency, but many normative studies of SVV have not screened for this condition [7,10,13,21].

SVV measurements are being increasingly used in the assessment of spatial cognition, to investigate otolith vestibular function and identify altered verticality perception as a possible cause of postural disorders in a range of conditions [22–26]. Faralli et al. have published that dynamic SVV test had a higher sensitivity compared to static test in diagnosing vestibular neuronitis (VN). Patients with vestibular neuritis appear to show more rapid normalization of static SVV than dynamic SVV, suggesting that dynamic SVV may be a clinically silent biomarker of central adaptation following peripheral vestibulopathies, and a complementary diagnostic test in the subacute stage of VN [6]. Given the similar SVV tilt values observed using the VIRVEST system, we predict that abnormalities in SVV in patients with peripheral and central vestibulopathies using this system would mirror those described elsewhere in the literature [22–26]. Further work using the VIRVEST system in patients with a range of vestibular and neurological conditions will be required to verify this. Moreover, there has been growing interest in understanding the mechanism of aging and its effect upon gait and postural control [17]. Age-related changes affecting the vestibular system have been demonstrated anatomically and physiologically [27–30]. The contribution of altered gravity perception in gait and postural instability in the elderly has not however been investigated. Given the increased sensitivity of the dynamic SVV with age, future studies using VIRVEST should assess dynamic SVV in the elderly and correlate this with postural instability and falls [7,8].

One significant advantage of the VIRVEST as compared to other SVV tools is the capacity to record a participant's behavior during each trial, and to review this later for offline analysis. This allows the tester to ensure that data has been appropriately acquired, and to assess the degree of certainty in the participant's responses. The tabulated data set allows the tester to visualize performed test values as well as short summary (average value, minimal and maximal values; see Fig. 5A). The graphical data output further details the temporal characteristics of the participant's behavior, showing how the participant approached the decision, and adjusted the angle of the vertical using the controller (see Fig. 5B). Such information uncovers the cognitive processes involved in SVV perception, which may be of clinical relevance in patients with specific neurodegenerative conditions.

We have also shown high SUS levels for the VIRVEST. There are several characteristics of the SUS that makes its use attractive: (a) it is composed of only ten statements and is therefore relatively quick and easy for study participants to complete and for administrators to score, (b) it is cost effective to use and can be scored very quickly, immediately after completion, (c) the SUS is technologically agnostic, therefore it can be utilized by a broad group of users to evaluate almost any type of user interface, (d) the result of the SUS is a single score, ranging from 0 to 100, and is relatively easy to understand by a wide range of people from other disciplines who work on project themes [15]. Moreover, the total scores also correspond with qualitative adjective ratings and help users to interpret individual SUS scores [16]. High usability scores of VIRVEST system were likely related to perspicuity and simplicity of use, requiring only two buttons to control the system with help of Gamepad modality or rather simple hand rotating movements in case of Myo gesture control armband. Both control modalities were used independently by participants after minimal instruction.

With an increasing application of VR technology in the biomedical sphere, there has been growing interest in the effects of vestibulo-somatosensory conflict induced by virtual reality on subjective dizziness, postural stability, and motion sickness [31]. Whilst increased motion sickness has been reported following 5 min of VR immersion, data shows that such symptoms decrease with adaptation to the stimulation delivered, such that it is less evident after 39 min of immersion [31]. The VAS is commonly used to evaluate patient's symptoms of dizziness. Some studies show that in the VAS symptom severity is classified as mild when the score is between 0 and 3; moderate, between 4 and 6; and severe between, 7 and 10 [32,33]. Given a median VAS value of 0.7 in our study, the VIRVEST appears not to induce any meaningful dizziness.

We investigated the degree of VRID following exposure to 4 SVV tests and found no dizziness or mild levels of dizziness following VR SVV assessments. As expected, we found no significant differences in VRID between participants using the Myo armband and Gamepad controller devices.

5. Conclusions

VIRVEST is a mobile virtual reality based system for implementation of subjective visual vertical test, is accurate and applicable in the clinical environment. There were no statistically significant differences in SVV values during static, dynamic and virtual reality stimulus conditions, obtained using the two different controllers and the results are compared to those previously reported in the literature using alternative methodologies. Gamepad-based virtual object control method was preferred by the users. The tests were well tolerated with low dizziness scores in the majority of participants.

Conflicts of interest

The authors declare that they have no conflict of interest.

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