A System for the Measurement of the Subjective Visual Vertical Using a Virtual Reality Device

José Negrillo, Antonio J. Rueda, Carlos J. Ogayar, Rafael Lomas and Rafael J. Segura

Abstract

Background: The Subjective Visual Vertical (SVV) is a common test for evaluating the perception of verticality. Altered verticality has been connected with disorders in the otolithic, visual or proprioceptive systems, caused by stroke, Parkinson's disease or multiple sclerosis, among others. Currently, this test is carried out using a variety of specific, mostly homemade apparatuses that include moving planes, buckets, hemispheric domes or a line projected in a screen.

Objective: Our aim is to develop a flexible, inexpensive, user-friendly and easily extensible system based on virtual reality for the measurement of the SVV and several related visual diagnostic tests, and validate it through an experimental evaluation.

Methods: Two different hardware configurations were tested with 50 healthy volunteers in a controlled environment; 28 of them were males and 22 females, with ages ranging from 18 to 49 years, being 23 the average age. The Intraclass Correlation Coefficient (ICC) was computed in each device. In addition, a usability survey was conducted.

Results: ICC=0.85 in the first configuration (CI=0.75-0.92), ICC=0.76 in the second configuration (CI=0.61-0.87), both with 95% of confidence, which means a substantial reliability. Moreover, 92.2% of subjects rated the usability of the system as "very good".

Conclusions: Our evaluation showed that the proposed system is suitable for the measurement of SVV in healthy subjects. The next step is to perform a more elaborated experimentation on patients and compare the results with the measurements obtained from traditional methods.

Key words: Subjective Visual Vertical (SVV), Diagnostic tool, Rehabilitation, Virtual Reality, Mobile application

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1. Introduction

In recent years, the number of eHealth and mHealth applications has increased significantly due to the advances in mobile devices and emerging technologies like virtual and augmented reality. In a recent study, Ramirez et al. [1] concluded that 86% of users were interested in using mobile applications to improve their health. Of special interest are applications related to patient follow-up, as they help in their recovery or in the treatment of chronic diseases (see Hernandez et al. [2], Abushakra and Faezipour [3] or Cho et al. [4]). Other interesting mHealth interventions include medical education, communication to and between health care providers, appointment or medication reminder and clinical diagnosis [5]. Among all these applications, our work focuses on the use of mobile devices and other emerging technologies as diagnosis and rehabilitation tools.

The measurement of Subjective Visual Vertical (SVV) is one of the most common tests for the evaluation of the perception of verticality in clinical practice. Biases in this perception are frequent after stroke [6], in patients with Parkinson's disease [7], or multiple sclerosis [8, 9]. Abnormal values of the SVV have been correlated with several peripheral vestibular disorders as the benign paroxysmal vertigo [10-12]. Kumagami et al. [13] also found abnormal tilts of SVV in patients suffering vertigo attacks caused by Ménière's disease.

The SVV test consists of adjusting a random-oriented line to the vertical position. The initial orientation is usually between 30 and 60 degrees right or left. The patient, seated and in a comfortable position, has to align it to the vertical position without any external visual reference. This posture allows the specialist to help in case the patient cannot maintain the correct position by himself. The consensual values, considered as normal for SVV, are between -2.5º and 2.5º with respect to the actual vertical [14].

The SVV can be static or dynamic. When the line is shown in front of a plain (usually black) background, the test is named static. On the other hand, if the background shows moving circles or other shapes, the test is called dynamic. Depending on the device used, the interaction paradigm changes.

In this article we present a diagnosis solution based on virtual reality and mobile technologies that can implement many visual tests and exercises commonly used in Medicine and Physiotherapy. Currently, we have focused on the SVV in its static modality but we have also implemented the dynamic method, the subjective visual horizontal (both static and dynamic) and an optokinetic stimulation exercise for vestibular rehabilitation.

This paper is organized as follows: First, current available methods for the measurement of the SVV are explained. Next, the architecture of our solution is described in depth, including the required hardware and the server and client applications. The following section details the experiments and usability tests used to validate this new tool. Section 5 shows the results of the validation. Finally, we present our conclusions and future work.

2. Previous works

Many different methods have been proposed for the SVV measurement. Piscicelli and Pérennou [14] made a survey about these methods. The most common approach is the bucket test method, proposed by Zwergal et al. [15]. In this method, patients estimate the vertical orientation by attempting to properly align a straight line visible on the bottom of a bucket that is rotated randomly by the examiner (Fig. 1.a-b). The line is formed by the light which enters through a groove done in the bucket bottom. A slightly more elaborated method uses a hemispheric dome

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with a surface of 60 cm in diameter that extends over the entire visual field with a random pattern of colored dots, providing no cues to gravitational orientation (Fig. 1.c). A linear target is fixed on the shaft of a servomotor and a computer is used to record the difference between the line and the true vertical. The visuo-haptic vertical protocol consists of manually orienting a metal rod with 10 red diodes. A potentiometer displays the angle between the true and the perceived vertical [18-20]. The rod and frame test [16] requires the orientation of a luminous line on a distracting background (Fig. 1.d-e). Finally, a few more protocols use a mechanical luminescent rod [21], or a luminous line projected on a wall [17] or displayed on a computer screen (1.f).

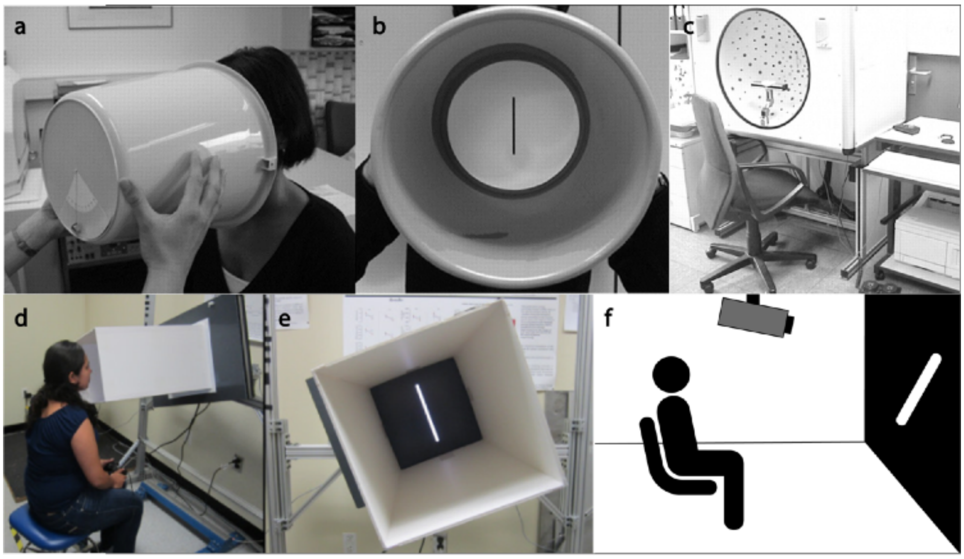

Figure 1. Different paradigms used in the measurement of the SVV. a-b: bucket test [15]. c: hemispheric dome method [15]. d-e: rod and frame test [16]. f: homemade protocol based in a projector [17]

As can be seen from description above and Fig. 1, several of these devices take up much space in the room, are custom built by hand, limit patient movement or require a dark room. Moreover, in several methods the measurement is recorded by direct observation of a scale, and therefore they may be subject to a significant observational error. Finally, most of them are specific for the measurement of the SVV and do not allow other diagnostic tests. Some companies, like GAES (a Spanish international company), provide commercial compact devices for this measurement [22], although their applications are specific to a single test.

Our goal is to provide a simple and affordable system based on mobile virtual reality to perform multiple tests and exercises related to visual perception that require isolation from the environment. The main advantages of our system are outlined below:

- **Flexibility.** The system provides several customization options for each test or exercise, that can be set by the specialist.
- **Versatility and extensibility.** Currently the SVV measurement and several additional tests and exercises are implemented. Its extensible architecture allows new tests and exercises to be added.
- **Price.** The proposed system is inexpensive, compared to several alternative approaches.
- **Precision and accuracy.** Mobile sensors provide high measurement precision and accuracy.

- **Size.** Required hardware does not need a fixed installation and takes up little space, in contrast to several of the tools described above.

Recently, Totiliene et al. [23] have also independently developed a mobile virtual reality-based system to solve some of the problems noted above. Unfortunately, they give few details about how static and dynamic SVVs are effectively measured. The experimental validation of the method has also been done with a modest number of subjects (15) and they have not studied the influence of using different hardware in the SVV measurement. We believe our description of an effective SVV measurement tool based on mobile virtual reality is more comprehensive, and we have addressed important issues as the study of the implicit errors in the mobile orientation sensors, that could affect the accuracy and validity of the method, and the implications of using a small digital screen (e.g., aliasing problems). Finally, we have conducted a more complete experimentation to assess the validity of the proposed system.

3. System description

This section describes the proposed system, such as the architecture and technologies used, the interaction paradigm with the patient, and the clinical tests and exercises implemented.

3.1. Architecture

Our SVV measurement tool uses a Google Cardboard [24] compatible headset, a smartphone and a bluetooth joystick. Google Cardboard is a low-cost virtual reality platform based on a custom headset that holds an Android or iPhone mobile. An app implemented using the Google VR software development kit displays a stereoscopic view, and the head movements are captured by the smartphone built-in orientation sensors. In our case this app shows a simple scene with a line to the subject and captures their interaction using the joystick.

Although the simple system described above would be sufficient for achieving our goal, we thought of a more flexible and powerful client-server architecture. A web application in a desktop computer (server) is used by the specialist in order to launch the tests in the mobile device (client) and collect the results (Fig. 2). Initially the device client application is in standby mode, waiting for the server requests. A request includes information such as the chosen test, its configuration parameters and the number of repetitions. After the test concludes, the results are sent back to the server, where they are stored in the patient's file and can be analyzed by the expert. Consequently, this approach has the advantage of avoiding a direct manipulation of the mobile device to launch a test, that may introduce undesirable delays and annoy the patient by putting on and taking off the headset multiple times.

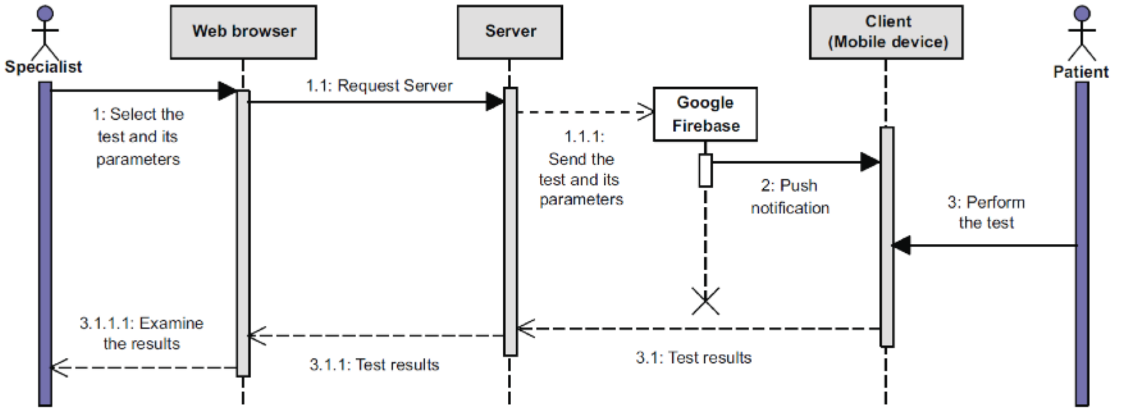

Figure 2. Sequence diagram of the complete system with all communications.

Commonly, the SVV is determined by the average of several tests (usually 3). Therefore, the resultant measurement (*res*) is determined by

$$res = \frac{\sum_{i=0}^{n} \delta_i}{n}$$

$$\delta_i = \alpha_i - \varepsilon$$

where δ_i is a single experiment result, α_i the angle of the line to the vertical, ε the constant implicit device error and *n* the number of tests performed. Note that the Google VR engine automatically detects the angle of the subject's head to the vertical and cancels it, so that during the tests the subject always sees the line in the same near-vertical orientation. Unfortunately, this introduces an error (ε), due to the limited precision of the orientation sensors of the device that must be considered. A detailed discussion of the inherent errors of orientation sensors in mobile devices, and their suitability for measuring biometric identifiers can be found in *Appendix I*.

A configuration page in the web application allows the registration of new mobile devices, by scanning a QR-Code with the client application. This QR-Code contains the IP of the server, enabling the client to access and register using a REST API. The communication from the server to the client uses push notifications provided by Google Firebase [25] (formerly Google Cloud Messaging). The device is registered to this cloud-based platform which manages all the transactions with a token-based communication system. Despite communications are encrypted, we implemented an extra secure layer since we deal with sensitive patient medical data.

The following section explains the interaction between the system and the patient as well as several critical aspects such as screen and visual quality.

3.2. Patient-system interaction

The client application initially shows an inclined line similar to the approaches reviewed in Section 2. Users use the bluetooth joystick provided to rotate the line to their subjective vertical position. Only three actions are allowed: turn left, turn right and done. This application was developed using the Unity game engine [26] which makes it easy to adapt the application to multiple platforms and implement new tests and exercises.

As we explained earlier, our virtual reality system requires a mobile device placed into the back of a headset and a Google Cardboard-enabled application to generate a pair of stereo images.

The lenses of the viewer are in charge of fusing both images to produce the 3D illusion. But even though the stereopsis is not required for measuring the SVV, the Google Cardboard framework provides a stereoscopic visualization by default. During our experiments a few users experienced problems to combine the two images in the brain. Fortunately we discovered that a scene covering the entire field of view (e.g., a field of stars) can help users in their stereoscopic fusion. This is shown during the waiting screen, before the test starts.

In addition, it is necessary that the screen has sufficient quality to achieve a good isolation. The resolution and color are two important features in order to get this.

In a Google Cardboard headset, the mobile is placed relatively close to the eyes of the subject, therefore the screen should have a minimum quality to avoid unpleasant sensations during the test or abnormal results. AMOLED screens show the purest black color [27] because pixels are turned on individually in contrast to standard LCD screens. As a result, devices which implement the latter technology may suffer from color deficiencies (especially backlight bleeding). Screen size is a critical feature because the screen edges of smaller devices may fall into the field of view, helping as a vertical reference during during the SVV test. Based on our experiments, we concluded that the optimal screen size must be greater than or equal to 5.5 inches, although using a smaller screen the results are acceptable if the user cannot see the edges when the mobile is placed into the headset. The aliasing problem of digital screens can also have a very negative effect on the measurement of the SVV. This aliasing generates a generates a jagging effect in line borders (Fig. 3.a) that could serve as a reference for the actual vertical. Using higher resolution screens decreases but does not prevent the problem. Consequently we adopted the practical solution of replacing the solid line with several aligned circles, where the aliasing problem has a much smaller effect (Fig. 3.b). By default, the line consists of green circles, although the number and color of the circles can be configured according to the specialist's preferences.

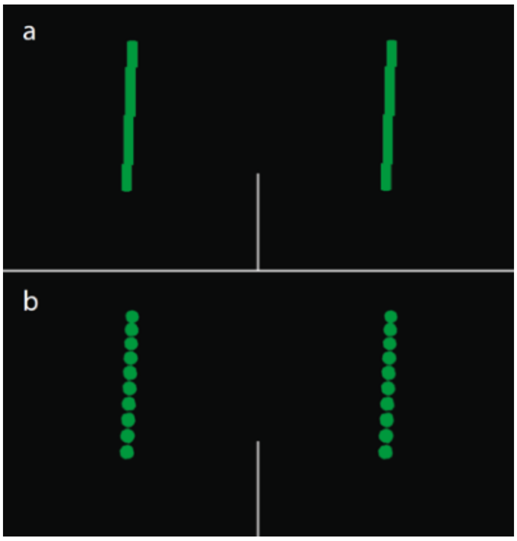

Figure 3. Visual comparison between a solid line (a) and a set of aligned circles (b). The jagging effect is accentuated when the line is near vertical position (a).

3.3. Implemented clinical tools

So far we have focused on the SVV test, but we have also developed two variants of the SVV: the Subjective Visual Horizontal (SVH), which consists of aligning a random-oriented line with the horizontal position, and the dynamic SVV test, which differs from the normal SVV in that the background shows a set of moving circles rotating around the center of the image (Fig. 4.a). The evaluator can customize the number, color, size, angular velocity and direction of rotation of the circles.

Finally, we also implemented the optokinetic visual stimulation, which consists of exposing the patient, without requesting any kind of interaction, to a set of moving multicolored disks, curtains or other objects for a predefined period of time (Fig. 4.b). The frequency, colors and shapes can be configured through the web application. Pavlou [28] studied the effects produced by incorporating this practice with other vestibular rehabilitation exercises and found that it improves dizziness, postural instability and symptoms of visual vertigo.

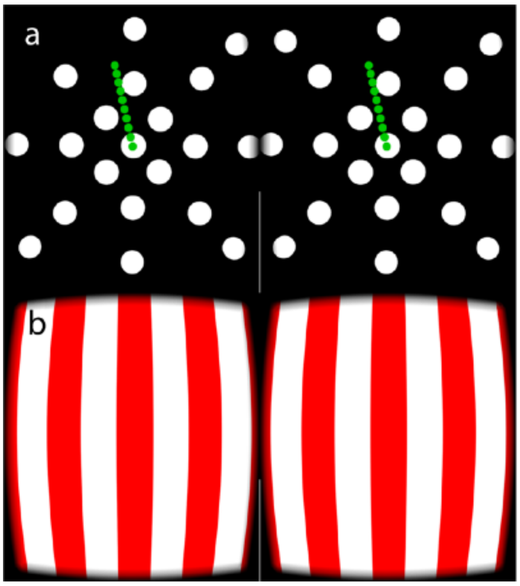

Figure 4. Screen-shot of the application running a dynamic SVV test (a) and the optokinetic visual stimulation exercise (b). Note: The distortion present in the image is corrected by the lens of the headset.

4. Method

An experiment was conducted to validate the system for clinical practice. For this purpose, 50 healthy students of the Physiotherapy Degree in the University of Jaén were recruited; 28 of them were males and 22 females, with ages ranging from 18 to 49 years, being 23 the average age. Informed consent was obtained from all individual participants included in the study. We have used two mobile devices for testing purposes: a medium and a high-end device. Their technical specifications are detailed below:

- **Medium device**. Its screen is a Quantum Color 5-inch and 294 ppi (pixel per inch) LCD screen. It is powered by a quad-core CPU running at 1.4 GHz with 2 GB of RAM memory.
- **High-end device**. The screen has the AMOLED technology and its size is 5.7 inch with 518 ppi. It has an octa-core processor running at 1.5 GHz with 3 GB of RAM memory.

In order to complete the experimentation equipment, two more components are required:

- **Laptop**. A standard computer with a web browser to access the control application. It is required to launch the tests on the mobile device and examine the results. This application was installed in a remote web server, accessible through the campus wifi network.

- **Two virtual reality headsets**. Two Google Cardboard compatible headsets made of hard plastic, with adjustable lenses and straps in order to maximize user comfort.

The procedure followed during the experimental sessions consisted of the following steps:

1. Three repetitions of the static SVV test in headset #1. This headset has the low-medium range device.
2. Same as in the previous test but using headset #2. This is equipped with the high-end device.
3. Usability survey of the proposed method.

The process to perform a SVV test (steps 1 and 2) is outlined below (see Fig. 5):

1. The subject is asked to sit in a comfortable position.
2. The expert teaches the subject how to operate the wireless remote control.
3. The subject puts on the headset and adjusts the straps to ensure a comfortable and firm fit.
4. The interocular distance and focus are properly adjusted by the subject to have the best visual quality during the test.
5. When the volunteer is ready the expert starts the test from the web application.
6. The subject rotates the line using the joystick until he perceives that it is close to vertical, and then confirms the result with an action button. This process is repeated as many times as the specialist has determined.

Figure 5. An experiment performed in a subject with our system.

After the experimental data was collected, we assessed reproducibility of the results obtained with each device. First, the Intraclass Correlation Coefficient (ICC) by Shrout and Fleiss [29] was calculated from three measurements of each phone. To assess reliability between the devices, the averages of the measurements of each device were obtained and the ICC was calculated from the two averages. For the first case, a two-way model was used, calculating the degree of absolute agreement among measurements by estimating the reliability of single ratings and averages of *k* ratings. To assess reliability between the devices, the one-way random effects model was used. Reliability is considered poor when the ICC is less than 0.40, moderate between 0.40 and 0.75, substantial between 0.75 and 0.90, and excellent above 0.90 [29]. Additionally, Bland-Alman plots were made to determine the limits of agreement [30]. In order to assess the clinical accuracy of the measurement, we calculated the Standard Error of Measurement (SEM) using the ICC as r_{xx} [31] and the Minimum Detectable Change (MDC) with 95% of confidence [32].

4.1. The usability survey

As mentioned before, a survey about usability was performed. It consisted of 10 questions and the answers are in a numeric scale between 1 and 5 [33, 34] where the value 5 is the best opinion.

1. Does the image refresh smoothly when interacting with the application?
2. Rate the degree of isolation from the environment during the test.
3. Is the visual quality of the scene sufficient?
4. Have you been able to fuse the images of both eyes correctly? (i.e., did you see one single image?)
5. Have you felt any dizziness during the test?
6. Did you feel limited in movement when you were wearing the headset?
7. Has the headset been comfortable for you?
8. Do you have any previous experience using virtual reality applications?
9. Is the application intuitive and easy to use?
10. Is it easy to learn how to use the application?

5. Results and discussion

For the device 1 the ICC=0.85 with 95% CI=0.75-0.92 and for the device 2 the ICC=0.76 with 95% CI=0.61-0.87 (CI stands for Confidence Interval). These results point to a substantial reliability in both cases. Between-device reliability shown an ICC=0.67 (95% CI=0.41-0.83) that implies a moderate reliability. The SEM and MDC yielded values of 0.90 and 1.76 for the device 1 and for device 2 the SEM=0.92 and MDC=1.80 (see table 1). Bland-Alman plots for device 1 are showed in Fig. 6.a-b, for device 2 in Fig. 6.c-d and between devices agreement in Fig. 6.e.

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Table 1: Reliability study of our proposal.

	Device 1	**Device 2**	**Between means**	**All measurements**
Number of subjects (*n*)	29	29	29	29
Number of raters (*k*)	3	3	2	6
Selected raters	The same for all subjects	The same for all subjects	Random for each subject	The same for all subjects
Model	Two-way model	Two-way model	One-way random effects model	Two-way model
Type	Absolute agreement	Absolute agreement	Absolute agreement	Absolute agreement
ICC Single Measures	0,8511 (CI=0,7467-0,9211)	0,7579 (CI=0,6071-0,8674)	0,6686 (CI=0,4093-0,8287)	0,6739 (CI=0,5356-0,8027)
ICC Average Measures	0,9449 (CI=0,8984-0,9722)	0,9038 (CI=0,8226-0,9515)	0,8014 (CI=0,5809-0,9064)	0,9254 (CI=0,8737-0,9606)
SEM	0,90	0,92	1,10	--
MDC	1,76	1,80	2,16	--

This table shows the details of the experimentation and the results of the reliability study. 29 subjects were tested using the two available devices. The rest of them only performed the test using the first device.

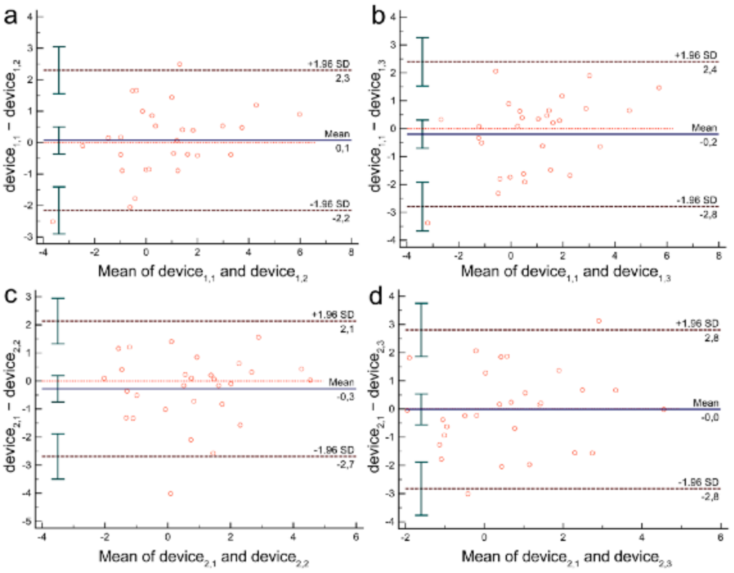

Figure 6. Bland-Alman plots. (a,b) are related to device 1, (b,c) to device 2 and (e) between means of both devices.

5.1. Performance

The client application runs smoothly in all the devices used. The framerate during the experimentation was always over 60 frames per second. Users have rated the smoothness of the application with a score over 3 in a 1-5 scale in 98% of cases.

The limited battery of mobile devices must always be taken into account when developing an application. Battery consumption mainly depends on how long the screen remains active. Although our application requires real-time stereo graphics and orientation sensor data, several techniques were used to make it as battery-friendly as possible, as limiting the frame rate in non-interactive scenes or using a dark background. The devices used in our experiments were actively used during the entire sessions, averaging two and a half hours of operation without recharging. This is an uncommon situation and during normal clinical practice, the device will be in standby mode most of the time.

Client-server communication only requires a simple intranet/Internet connection from the client to a web server and the performance is good as the communication is based on short text-based messages.

5.2. Usability

After the experiment sessions, 92.2% of subjects rated the usability of the application with 5 (being 5 *very easy* on a scale of 1 to 5). Besides, the application was considered very intuitive for most subjects (96% of them valued it over 4 in the same scale). More than half confirmed that this was their first experience with a virtual reality application (56.9% of the sample taken).

A complete isolation of the environment is a requirement for the SVV and the rest of tests. 98% of users valued it over 3 on a scale of 1 (*poor isolation*) to 5 (*total isolation*). We realized that depending on the room illumination, some light could enter through several holes of the virtual reality headset. A simple solution could be to print several rubber caps with a 3D printer in order to close these holes.

5.3. Comfort tests

The virtual reality headset is designed with comfort in mind. It has soft pieces around the nose and eyes to reduce pressure, adjustable straps and adaptable focus and pupil distance. In general, the headset is considered comfortable: 96% of volunteers rated it over 3 in a 1-5 scale and 92.2% do not consider it movement limiting.

The headset has enough space for the subject’s glasses, although according to our physiotherapy expert, wearing or not glasses does not affect to the SVV perception. We have allowed wearing it to improve image sharpness and to allow high-diopter people to use the proposed system.

As we noted in Section 3.2, the difficulties to achieve stereo fusion have been the main issue among the test subjects. In general, the problem appears only in the standby screen. Nevertheless, 86.1% of volunteers scored the fusion as *correct* or *almost correct*. Interestingly, most people that experienced fusion problems in our experiments also claimed similar issues in 3D cinema or TV.

Potentially, the main problem of the system could be the so-called virtual reality sickness. Factors like age, gender, postural instability, sensitivity to motion sickness or flicker in the display, or lack of previous experience with virtual reality systems are known to increase the risk of suffering sickness [35]. Nevertheless, only one person in the sample felt dizzy during testing (dizziness level 2 on a 1, *very dizzy* to 5, *not dizzy* scale).

6. Conclusion and future work

This work proposes a simple, flexible and affordable virtual reality-based system suitable for the measurement of subjective visual vertical. Additional tests and exercises have been developed, namely, dynamic subjective visual vertical, subjective visual horizontal and optokinetic visual stimulation. Its main advantage is its versatility since it allows to implement new tests and perception-related rehabilitation exercises easily. Using a mobile device also has the advantage of allowing the distribution of the application for rehabilitation of patients at home.

In the near future our plans include the implementation of more clinical tests related to visual perception and rehabilitation exercises. We are also studying using the same system to perform other tests not related to the visual perception like the standing balance and walking stability.

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Appendix I: Inherent errors and sensor precision

Our application requires reading the orientation of the mobile device to determine the actual vertical position and compare it with the patient's subjective vertical. Mobile devices determine their orientation using the accelerometers and gyroscopes integrated into the Inertial Measurement Unit (IMU). This unit provides information about positions and rotations with respect to the three coordinate axes. The position relative to the vertical is directly read from the Y rotation component of the sensor. However, there are several implicit problems related to the information provided by these sensors. First, all devices have an error when they are placed in vertical position. We observed a fixed deviation in the rest position between 0 and 6 degrees, depending on the device used. This sensor bias can be removed by introducing a calibration step in the application that only has to be done once, before the first SVV test. This process is done by placing the device on its side on a flat, firm and perfectly horizontal surface (e.g., a table). The correction value (ε) is automatically saved after the device has been stable for 3 seconds in the indicated position.

A second problem is related to the precision of these sensors. The gyroscope and accelerometer sensors in mobile devices were primarily designed for detecting portrait/landscape orientation changes, stabilizing camera, detecting gestures (e.g., shaking the device) or gaming. Using these sensors in new applications like trajectory reconstruction is challenging because of the impact of the cumulative sum of the measurement errors (see Wang et al. [36], Suvorova et al. [37]). In a similar way, their use for the measurement of biometric identifiers is an important issue. For this reason, we conducted an experiment to assess the precision of these sensors, and determine if a calibration/filtering process needs to be introduce to suppress errors.

For each device, we performed a static test for measuring how much the vertical calibrated position varies over the time. For this purpose, the device was held still in the same position as in the calibration process and one thousand vertical measurements were taken. Then, the average, standard deviation and variance were computed.

With a 99% of confidence, we can conclude that all devices keep the error below one decimal digit ($error < 0.1$) and 33% of them have more precision ($error < 0.01$ with 99% of confidence). This precision is totally acceptable for the measurement of the SVV so we use the deviation value approximated to the first decimal, without implementing any filtering. In addition, we observed that the measure is minimally affected by the wireless services of the device such as GPS, 3G/4G, bluetooth, etc. Precision improves if these services are disabled. However, this is not completely possible because our application requires at least a data connection is required for communicating with the server.

Compliance with Ethical Standards

Funding: This research was supported partially by the Spanish Ministry of Education, Culture and Sports via a doctoral grant to the first author (Ref. FPU16/01439).

Conflicts of interest: All authors declare that they have no conflict of interests.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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