# Vestibular Damage Assessment and Therapy Using Virtual Reality

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**Abstract.** Vestibular damage can be very debilitating, requiring ongoing assessment and rehabilitation to return sufferers to normal function. The process of rehabilitation can require an extended period of therapy during which patients engage in repetitive and often boring tasks to recover as much normal vestibular function as possible. Making these tasks more engaging while at the same time obtaining quantitative participation data in these tasks is critical for a positive patient outcome. Here we describe the conversion of vestibular therapy tasks into virtual reality and technology that enables their deployment in both directly- and remotely-supervised vestibular rehabilitation. This infrastructure is currently being evaluated in tests within a clinical setting.

**Keywords:** Virtual reality · Vestibular rehabilitation · Vestibular assessment

## 1 Introduction

Vestibular impairment can occur as a consequence of a stroke [5,12,14], concussion [1] or other head trauma [9]. Dizziness and related vestibular-like issues can also occur with no obvious physiological cause, especially in the elderly [10]. Vestibular impairment can be extremely debilitating, and if severe, can impair normal daily activities. One of the most critical functional behaviours supporting quality of life is mobility, and falls are one of the biggest threats to older adults' safety and mobility. One-third of older adults in Canada will fall at least once each year and one-quarter will experience a fall-related injury [16]. Dizziness and low vestibular functioning is an important contributor to this problem, and yet, methods of assessing progress in vestibular therapy rely largely on self-reporting.

Various rehabilitation therapies have been proposed to help restore normal vestibular function (see [6,7]) and are generally recommended in order to enable

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(a) Reference object view (b) Target object view

**Fig. 1.** The Find Target task. The patient first fixates the reference object (a), and then once this object is selected, must move their viewpoint to fixate on the target object (b). The possible locations of the target object are defined by the clinician and are set to exercise the patient's head motion and thus their vestibular system.

such individuals to return to their normal daily lives [17]. Many of the required therapies involve repetitive exercises that encourage adaptation to the underlying damage to the vestibular system. Monitoring such exercises, and in particular, ensuring that patients perform such exercises between visits to therapists is thus critical to improving patient outcome. Lack of adherence to these assigned exercise regimes usually comes down to two reasons: patient anxiety from lack of guidance or boredom from repetitiveness of exercises [13]. Gamification of therapeutic exercises can alleviate boredom by providing guided and personalized treatment progression from the safety and comfort of a patient's home [11,15], but even here, monitoring and refining of assigned exercises is critical to the outcome of the patient's recovery.

Here we describe an infrastructure enabling vestibular stimulation exercises that can be carried out either under direct supervision within a clinical setting or between clinical visits at the patient's home. The same virtual reality infrastructure can be used as a vestibular function assessment tool. The system described here utilizes commodity virtual reality hardware (the Lenovo Daydream Mirage Solo) and software tools (Unity) integrated with a cloud-based system providing control of rehabilitation tasks and their settings as well as data collection from individual patient sessions. Although testing to date has concentrated on supervised clinical testing with a trained physiotherapist in attendance, the long term goal is be develop a system that can be used by patients under remote supervision.

## 2 Exercise Treatments

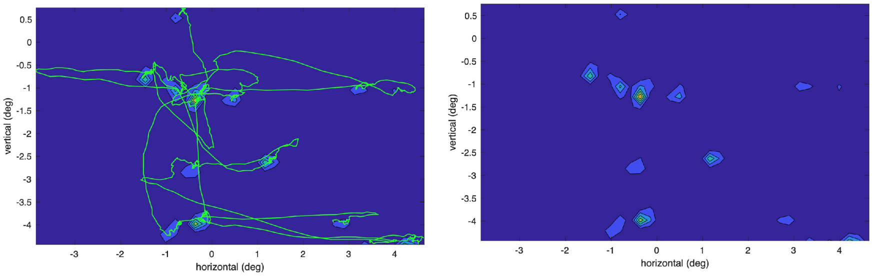
In order to enable patients' engagement in vestibular exercises at home, many tasks are designed to be straightforward and utilize material that is readily available. For example, a task might require a patient to fixate playing cards that have been secured to the walls of a patient's home and then to make head motions that cause the patient to move their head so that it is directed at different cards. Recognizing the need to transfer existing vestibular exercises and also recognizing the limits of commodity virtual reality hardware, we concentrated initially on two exercises that require the patient to produce head motions in a controlled manner. In particular, as the commodity head mounted display used in this study lacks eye tracking, only tasks that rely on head motion have been evaluated to date. The pen-and-paper version of traditional exercises are performed using household items (e.g., a deck of playing cards and painter's tape to mount these cards on a wall) and the task is made more challenging as the patient recovers. For example, as the patient progresses the distance to the wall is changed, more complex wall textures are used, and the subject may conduct the experiments while sitting on an exercise ball. Here we concentrate on two such exercises, one in which the patient must search the visual space to find a target and one in which the patient must move their head to choose between two different targets. We refer to these exercises as *Find Target* and *Choose Target* which are described below.

For both the exercises described below, a given treatment consists of a sequence of localization tasks with a common theme (Choose Target or Find Target). These exercises consist of a sequence of steps with similar simulated room sizes and visual complexity. Specific parameters that can be set for a given step in a trial include:

- **Room type:** Simulated rooms can either be small or large and can be either "unstructured" or "textured." Unstructured rooms are bare with just a door, walls, floor and ceiling. Textured rooms are decorated. Larger rooms allow for larger head rotations and are thus more suitable for advanced patients. Visual complexity of the background adds to the difficulty of directing the head towards the target.
- **Number of trials:** The number of trials that appear during the step. As patients progress, more trials are added.
- **Trial timeout:** The maximum duration of a trial in a given step. If the patient does not complete a trial correctly within this time then the trial is counted as having failed and the next trial begins.
- **Monocular/binocular presentation:** Clinicians have the option of presenting targets in only the left or right eye, if desired.
- **Target population:** The collection of targets that will be used in a given trial. Smaller scale targets are used for more advanced patients with mild hypofunction, and larger targets are used for those with more severe hypofunction.
- **Target space:** In Find Target, choose the direction of the target object relative to the reference object (horizontally, vertically, or diagonally displaced.) For Choose Target, choose where a target object and a distractor object are relative to one another (horizontally, vertically, and diagonally displaced).

### 2.1 Find Target

The Find Target exercise is a head movement exercise treatment in which a patient moves their head from a neutral position indicated by the reference




(a) Head motions (b) Motion heat map

**Fig. 2.** Tracked head orientation during the find target task. In (a) multiple trials are shown, each with a track that begins approximately at (0,0) and moves to the orientation of the target to be found. (b) shows a heat map of the dwell time at each head orientations over multiple trials.

object to point towards a location indicated by a target object (see Fig. 1). In the pen-and-paper exercise, target objects can be represented by playing cards or pieces of paper with writing either held in the clinician's hand or taped to a wall. The target may be horizontally, vertically, or diagonally displaced relative to the neutral head position, depending on the type of hypofunction and treatment goals. When the patient is comfortable repeating this activity for 1–2 min, the task can be made more complex. For example, the object can be placed against a visually complex background, such as patterned wallpaper or a dynamic background such as a television screen. Patients progress from a seated position, to seated on a stability ball, to standing, to standing on soft surfaces or on one leg.

The virtual reality version of this task is illustrated in Fig. 1. Here the user is placed in a virtual environment and the reference target (a 3d placeholder) is rendered directly in front of the patient. The patient fixates on the reference object and presses a button using a wand when the reference object is fixated. At this point, the reference object is replaced by a target object at some displacement relative to the reference object. The patient then moves their head around the space until the target is fixated and their head is pointing to the target and then presses a button using the wand to indicate that they have localized the target.

The pen-and-paper and the virtual reality-based version of this task perform the same basic treatment. The clinician identifies particular horizontal and vertical offsets from a "straight ahead" direction. The target object is placed in some direction that will cause the patient to move their head in a particular manner. In the pen and paper version of this task, the object might be playing cards taped to the wall. The card locations are fixed and patient performance is not recorded unless they are supervised directly. The virtual environment version provides the opportunity to personalize the environment and choose the objects to be displayed. The virtual reality version of the task also provides considerable

(a) Reference view in VR

(b) Target view in VR

**Fig. 3.** The choose target task. The patient first fixates on the reference object (a), and then once this object is selected, they must move their viewpoint to choose the target object (b). A distractor object is also presented in the virtual space. The possible locations of the target object are defined by the clinician and are set to exercise the patient's head motion and thus their vestibular system in specific ways.

information about the actions of the patient. Quantitative information about time taken, velocity of the patient's head motion, etc. are recorded. One critical advantage of the VR-based solution is that quantitative data concerning head motion is recorded "automatically" as a consequence of the VR nature of the rendering. For example, for the find target task, head directions can be recovered and a heat map of head orientation dwell times can also be recovered (Fig. 2).

## 2.2 Choose Target

Choose Target adds a second target to the Find Target task described above (Fig. 3). Adding another target allows a patient to practice moving their eyes and head between the two. Ideally, the additional target is placed just inside their periphery so they can move their focus between the two such that only a single target is clear at any given time. These objects can be separated horizontally, vertically or diagonally relative to one another.

These target exercises allow for one target to be placed directly in front of the patient, and the other, for example, to appear over their left shoulder or over their right shoulder, all at eye level. While seated the patient looks from one target to another. Only one of the two targets is the same as the reference target which is the one that must be looked at. The other target is a distractor. As the displacement between the two targets is increased the patient must make larger and larger head motions to bring the correct target into view. The controlled direction of separation between the two test targets forces the patient to make head motions in the desired directions when performing the task. As with the Find Target exercise, once the patient is sufficiently comfortable carrying out the exercise seated and with the targets against a neutral background, they may progress to gradually more complex backgrounds, or to standing on one or both feet, or seated on a stability ball.

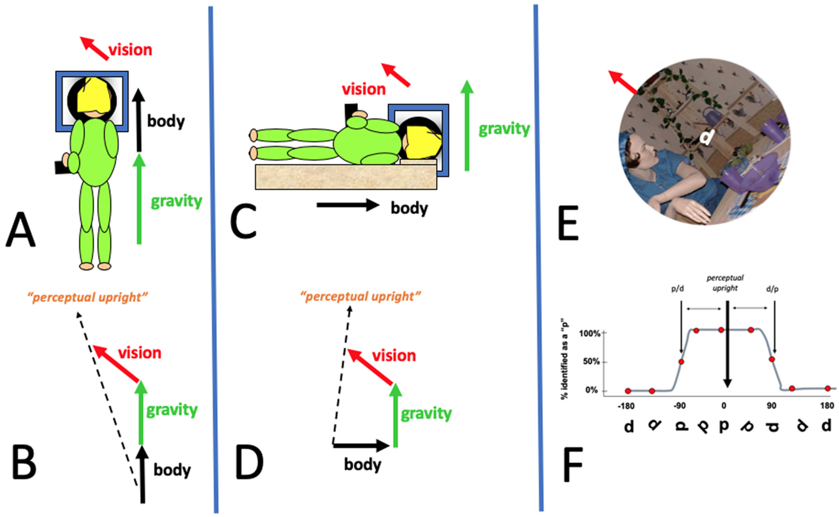



**Fig. 4.** The OCHART test. Observers view a screen arranged so that nothing outside the circular display (E) is visible either when upright (A) or lying on one side (C). The display (E) shows a highly polarized scene with a clear upright. Superimposed on this image is the probe character (p/d) and the participant's task is to simply respond as to whether the character looks more like a "p" or a "d". By plotting the percentage of time, one interpretation is chosen (F), and the points of ambiguity can be determined. The perceptual upright is defined as being midway between these orientations.

## 3 Measuring Vestibular Function

A final step in providing personalized VR-based vestibular treatment is a mechanism to quantify the current state of vestibular information processing. In 2006, Dyde, Jenkin and Harris [4] developed a quantitative measure for estimating the relative importance of the main factors that determine the perceptual upright using visual probes presented to an observer while they were in different body positions. By separating upward sensation signaled by the bodily, gravity and visual cues, we were able to quantify their individual contributions. This tool, known as OCHART (the Oriented CHAracter Recognition Test), has proven successful in estimating a subject's perceptual upright and the relative contributions of vision, gravity and the body to that estimate (e.g., [2,3,8]). The OCHART test uses a character – the identity of which depends on its orientation. The perceptual upright is defined as the orientation of that character at which it is most unambiguously identified. To find this orientation, the points of greatest ambiguity are found (at which the character is equally likely to be identified as either interpretation) from which the orientation of least ambiguity can be deduced (Fig. 4).

The perceptual upright can be modeled as the sum of three vectors corresponding to the orientation signaled by visual cues, gravity cues and the internal

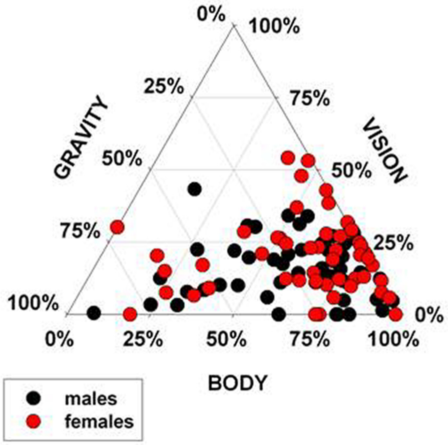



**Fig. 5.** The relative contribution of vision, gravity and the body in a large group of neuro-typical participants.

representation of the body [4]. By testing in at least two body orientations, (e.g., upright and on one's side, Figs. 4 A and C) the relative lengths of the vectors corresponding to the contributions of the vision, gravity and the body can be calculated using simple geometry. The direction of the perceptual upright can be modeled as the sum of three vectors corresponding to the directions of upright signaled by the visual display, gravity, and the orientation of the body (B and D) from which the relative lengths of the vectors can be calculated, corresponding to the relative contributions of body, gravity and visual cues to upright. Figure 5 shows the relative contributions of visual, bodily and gravity cues for a large sample of neuro-typical participants. The diagram is a ternary plot in which the percentage contribution of each source of information is plotted on each of the axes. This is possible because the contributions are relative to each other and therefore sum to 100%. What can be seen is that the data cluster in the bottom right corner of the diagram indicates the typical contributions of vision (around 20–25%), gravity (10–20%) and the body (>50%) to the perceptual upright. Note that even in this normal population there are some outliers with high contributions of vision or gravity cues (>50%).

## 4 Managing Users and Treatments

As modern HMDs like the Lenovo Mirage Solo incorporate an integrated computer with WIFI access, it is useful to exploit this capability in order to control treatment plans on individual devices. Patients register a given HMD with a web-based server and clinicians manage their patients and their patients' treatments using a web application. The front end of the application was created using the Angular web application framework and the Angular Material component library. The back end server exchanges and stores data to and from the

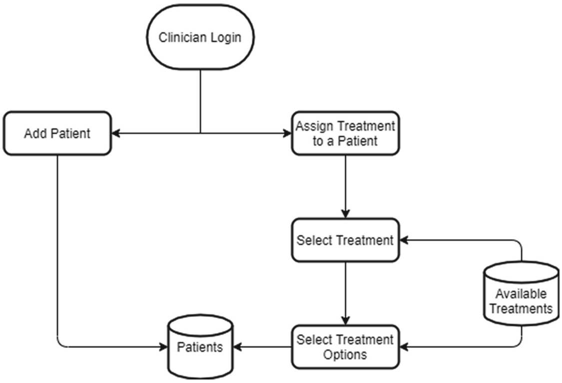



**Fig. 6.** This is a diagram detailing the intended workflow of a clinician using the treatment management web application.

front end and HMDs. It was implemented using Node.js, written in TypeScript with the Express.js framework, and uses MonogoDB as the database.

Clinicians provide treatments to patients following the workflow illustrated in Fig. 6. A calendar view provides a convenient mechanism for clinicians to view upcoming treatments, to customize treatments for specific patients, and to review patient performance.

## 5 Ongoing Work

The technical infrastructure described here is currently being used in a clinical setting to explore the acceptance of the approach by patient populations and to better understand how clinicians might best deploy the technology both in a directly supervised mode as well as remotely. This final case being of particular interest given the ongoing global pandemic and the interest in being able to provide remote treatment for populations not in close proximity to a treatment centre. As part of this process, we are exploring the development of additional treatment mechanisms including treatments that rely on eye tracking capabilities of the HMD. (A number of manufacturers provide such functionality.) We are also porting the technology from the Lenovo/Daydream platform to the Oculus platform given the lack of ongoing support for Daydream in the commodity market. As the HMD infrastructure leverages standard tools, such as Unity for rendering, and standard networking tools for interaction, this process is relatively straightforward.

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