Virtual reality in vestibular diagnosis and rehabilitation

D Alpini[1], L Pugnetti[1], L Mendozzi[1], E Barbieri[1], B Monti[1] and A Cesarani[2]

[1]Scientific Institute S. Maria Nascente, Fondazione don Gnocchi, via Capecelatro 66, 20148 Milan, ITALY
[2]University of Sassari, Institute of Otolaryngology, via Mancini 5, Sassari, ITALY

[1] *melau@tin.it*

ABSTRACT

While vestibulo-oculomotor and vestibulo-spinal functions are usually investigated by means of electronystagmography and stabilometry, environmental exploration and navigation cannot be easily studied in the laboratory. We propose that virtual reality (VR) can provide a solution, especially for those interested in the assessment of vestibular influence over spatial cognitive activities. Subjects exposed to immersive VR show rotatory behaviors during exploration that are the result of both a lateralized vestibular dominance and of the interplay with ongoing cognitive activity. The effect of vestibular dominance over exploratory behavior disappears in non-immersive VR conditions, but certain patterns of exploratory movements still seem to be associated to cognitive performance. On these grounds, we propose the use of VR to improve current techniques of vestibular rehabilitation based on visual feedback. We describe a new equipment that combines the functions of a digital stepping analyzer with those of a PC VR workstation. The patient controls the navigation of virtual environments by means of appropriate displacements of the center of gravity. The combination of a closed-loop feedback to control displacements of the center of gravity and active exploration of the environments makes an otherwise static exercise contingent on a viridical representation of spatial navigation.

1. INTRODUCTION

Human equilibrium is a complex psycho-sensory-motor function which serves a number of purposes, such as exploration of the environment (using visual informations via oculomotor control), maintenance of a desired body position against the force of gravity (posture), and movement within the environment against the force of gravity (walking, running, jumping,..).

The role of the vestibular system in equilibrium is to integrate multisensorial cues from the eyes (Kohen-Ratz, 1977), the labyrinths and proprioreceptors and to provide a continuous neural representation of both segmental body orientation, i.e. the position of body segments relative to one another, and orientation of the body within the environment (spatial orientation) (Andersen et al., 1993). Orientation is, therefore, the basis of any correct motor behaviour, including the exploration of the environment. In fact, the latter can be conceived as essentially an ocular-motor affair in which the head and the body help overcoming the constraint of a narrow field of view. Our abilities to localize objects in a space, orient relative to them, move toward or away from them, reach and manipulate them, all depend critically on receiving, processing and integrating spatial information from gravity, the visual field, and our own body. The vestibular system provides the multisensorial integration that serves to maintain a stable map between spatial localization, spatial orientation, and physical space (McNaughton, 1987).

While vestibulo-oculomotor and vestibulo-spinal functions are usually investigated by means of electronystagmography and stabilometry, environmental exploration cannot be easily studied in the laboratory. Virtual reality (VR) can provide a solution for the assessment of vestibular influence over spatial cognitive activities such as orientation and navigation.

This paper introduces ongoing studies dealing with vestibular-mediated behavior during the exploration of virtual environments and outlines the rationale for the use of VR as an assistive tool to retrain vestibular function.

2 .VESTIBULAR ACTIVITY AND THE EXPLORATION OF VIRTUAL ENVIRONMENTS

Although the interaction that can take place in a virtual environment (VE) is still limited to a small variety of relatively simple motor activities, an important advantage is that the latter can be planned and executed as in a real space. The activity of the vestibular system is generally discussed in the framework of immersive VR experiments (Stanney et al., 1998). However, some features of exploratory behavior in non-immersive conditions could also be interpreted as the expression of vestibular mechanisms. This hypothesis is based on the non-randomness of turning behaviors of healthy and impaired subjects in different experimental settings.

A simple manouvre is used clinically to show that vestibular activity is lateralized. Subjects are asked to perform a simple 180° rotation from a standing upright position. This movement has no explicit purpose and is performed in the real environment and repeated a few times. The direction (rightward or leftward) of each rotation is noticed. As this test was performed by a group of 50 healthy individuals and by two matched groups (n. 25 subj. each) of adults suffering from right or left vestibular dysfunction, subjects with normal vestibular function showed a clearcut preference for rightward rotations, which we interpreted as a sign of lateralized vestibular dominance. This conclusion was supported by the finding that in subjects with left vestibular hypofunction the preference for rightward rotations was less but still visible, while in subjects with right vestibular hypofunction a prevalence of leftward rotations was observed .

The exploration of a VE wearing a headset connected to a tracking device (immersive VR setup) provides a unique opportunity to study spontaneous head and body rotations performed during the course of a cognitive activity. In a recent experiment (Alpini et al., 1996) 39 healthy righthanded subjects, aged 22 to 43 were asked to carry out a cognitive task in an immersive VE. Subjects sat on a revolving chair in order to avoid postural stance preferences and muscle fatigue during the VR session. Sideward rotation of the head and/or the whole body triggered a counterclockwise displacement of the visual image to simulate the natural change in viewing angle and to allow a 360° exploration of the environment. The latter was made of decagonal rooms connected by corridors. Each room had 5 doors of different shape and color located on alternate walls. We asked subjects to select an exit door only after they had carefully observed the entrance door. Hence, as they entered a new room, they had necessarily to turn 180° to observe the door which they had just passed through and then turn again to make the appropriate selection. To do this, subjects were free to rotate clockwise (rightward) or counterclockwise (leftward). Each subject explored a total of 32 rooms, which took an average of about 30 minutes. The first two body rotations after entering each room were classified as rightward or leftward turns. The analysis showed a prevalence of clockwise movements (rightward) on both the first and the following (back) movement. The majority of events occurred as a combination of back and forth turning movements (Right-Left and Left-Right). Only a few instances of right-right (R-R) rotations and even less of left-left (L-L) rotations were seen. We have then looked at turning behavior. Subjects were then divided into three groups according to their cognitive performance: good (9 subjects), average (15 subjects), and bad performance (15 subjects). Subjects in the first group were both fast and accurate while subjects in the third group were the slowest and made many selection errors. Subjects in the first group showed a clearcut preference for leftward rotation on the first movement followed by a rightward return. Subjects in group 2 did not attain a "preferred" turning behavior until room 15, whereas subjects in group 1 did it much earlier. Group 3 subjects did not show a clearcut preference for any of the two heterologous turning behaviors. As for the clinical diagnostic manouvre, rotations in the VE were not guided by the necessity to explore, but rather to follow an instruction. In other words, subjects got important visual information for the task they were carrying out only after rotation was over, not during rotation. This experiment suggested that immersive VR should be further investigated as a tool to assess in the laboratory vestibular function during exploratory activity. It also confirmed the interplay between ongoing cognitive activity and seemingly pure automatic behaviors (preselected sensory-motor schemata) such as turning backwards.

The use of an immersive VR setup, however, may not be safe or practical for some subjects (Stanney et al., 1998). Cybersickness is an obvious contraindication. Therefore, in a further experiment we asked 26 healthy subjects to explore four rooms of a virtual house by handling a joystick while watching a 17” color PC monitor (non-immersive VR) (Pugnetti et al., 1998); this setup is known to reduce the risk of VR side-effects (Stanney et al., 1998). The task was to search for an object which, in fact, was not there. In this condition, the exploration is based on pure ocular-motor strategies that can be inferred from the direction of rotation of the virtual environment caused by lateral bends of the handle of the joystick. This, of course, excludes any direct stimulation of the labyriths and neck proprioceptors and has some analogy with the exploration of space which occurs during smooth driving. Nine of the subjects explored first the right hemispace after entering each of the four rooms, 10 subjects preferred a leftward exploration, while 7 subjects made rightward and leftward explorations in various combinations. The latter showed a significantly better recall of objects present in the virtual rooms than the former two groups.

Though still incomplete, these findings suggest that the lack of a direct involvement of the afferent systems involved in head turning reduces the expression of a lateralized vestibular dominance; another hypothesis worth of further study is that smooth shifts of the field of view performed to get continuous visual information (true exploratory rotations) also reduce the expression of vestibular dominance, i.e. visual processing takes precedence over orientation. However, in both immersive and non-immersive VR conditions there seems to be an interaction between certain rotation patterns (i.e. vestibular activity) and cognitive performance (Alpini et al.,1996).

3.VIRTUAL REALITY IN VESTIBULAR REHABILITATION

Vestibular rehabilitation is a well known technique that combines physical and instrumental exercises to reduce vertigo and dizziness caused by a vestibular dysfunction. Instrumental rehabilitation is usually based on stabilometry: a platform records the shifts of the center of gravity (CoG) of a standing subject who is made aware of them and improves his static equilibrium through visual feedback on a computer screen (Kohen-Ratz, 1977). The assumption is that when the patient regains control over his own CoG, then he will be able to transfer this benefit to the largely automatic control of CoG necessary during dynamic activities of daily life. This is not always true. Navigation, for example, is a complex function that requires the continuous matching of internal and external landmarks in an automatic and unconscious way. Usually we have no conscious representation of the CoG as a "landmark", but we know that we are along the correct way because we compare the internal references (with special regards to the direction of gravity) with external visual references (Wapner and Witkin, 1950): a door, a wall, the horizon,... It follows that navigation strategies are different in closed and in open spaces and that the qualitative aspects of an environment such as lighting conditions, colours and obstacles influence spatial orientation and navigation.

Virtual reality represents a more specific tool to approach vestibular rehabilitation from an instrumental (feedback) perspective because it mimicks the experience of navigation and spatial orientation. Furthermore, VR allows motor performance (body control of the displacements in the virtual space) and cognitive performance (i.e. active exploration of the environments) to be combined in a variety of meaningful ways.

Here we outline the characteristics of the equipment we have used to get preliminary insights into this potential new VR application.

3.1 .Hardware

We combined a low-cost immersive VR workstation with a digital stepping analyzer (D.S.A.) to detect of head and trunk movements (Fig. 1). A modified joystick is attached to a platform on the floor and subjects control their movements inside the VE by voluntary displacements of their CoG while standing close to the vertical of the joystick. The sensitivity of the joystick to sideward bending of its modified handle can be calibrated and adjusted by an external command box. This allows to personalize the patient/VR interaction. The D.S.A has been developed by the Bioengineering Department of the don Gnocchi Foundation and is composed by a solid state camera placed 120 cm above the standing subject and providing a compound video signal at 50 Hz with a resolution of 625 lines. The camera is synchronized with the other components through a Video Sync Generator. The subject wears four refrangent 1 cm diameter hemispheres on the rignt and left shoulders, and on the front and the back of the head. The camera is equipped with a solid state sensor (CCD) with high black/white resolution and a 3.5 mm lens. Between the sensor and the lens an InfraRed filter (870 nm) cuts the visible components of the images. An InfraRed Flash with 120 LD IR and a 880nm emission makes the CCD sensitive only to IR images reflected by the markers. The video-images of the subjects and of the markers are then filtered and resynchronized. The resulting signals are elaborated by three counters (X,Y,D) connected and synchronized by a common clock. The counters provide X/Y coordinates for the first over-threshold pixel referred to each marker and the duration (D) of its state. X,Y and D informations are sequentially ordered and divided by a Multiplexer. In this way they are stored in a FIFO (First In First Out) buffer as paked 8 bit units. A Universal Asynchronous Receiver Transmitter (UART) connected with a standard serial RS232 port of a Pentium 100 PC, allows the transfer of data from the buffer to the PC at a maximum rate of 230.400 bit/sec. A specific C++ program running under Windows 95 controls the raw data flux from the DSA, the dynamic display during acquisition, and computes parameters and stores results in a database. Each trial requires at least 2Mb of HD memory to store the raw data.

The system proved to reliably recognize displacements of the head and shoulder markers in different conditions: standing, stepping, or performing any complex head and trunk movements, such as those required to navigate a virtual environment. Therefore, the system should make it possible to compare times and travelled distances in different subjects or in the same subject before and after vestibular rehabilitation.

Comparisons are based on the following main parameters:

- the lateral and longitudinal components of the velocity of each marker
- the absolute mean velocity of each marker (cm/sec)
- the lateral and longitudinal components of the displacements of each marker
- the total distance travelled by each marker; it is an estimate of the displacement of the subject into the virtual world
- the global displacement, which measures the absolute displacements of the subject in the real world

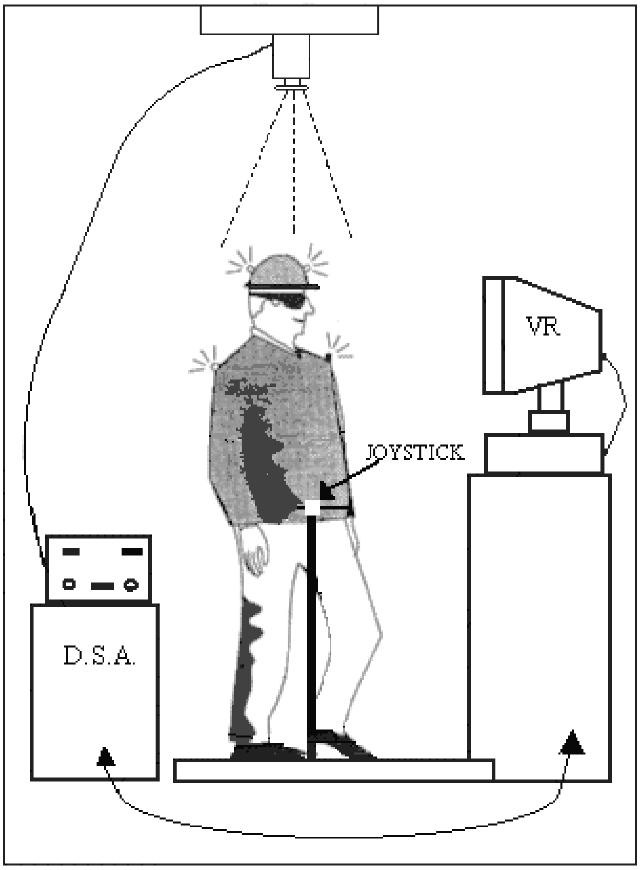


Figure 1. *A schematic drawing of the equipment for vestibular rehabilitation*

3.2 . VR Software

The two VEs currently used for vestibular rehabilitation were both developed under Superscape VRT. The first program features a green landscape with a few landmarks and scattered arrows that indicate the direction to travel. By displacing his/her CoG along antero-posterior and lateral directions by appropriate utilization of ankle-hip strategies, the trainee must follow an invisible path that connects an arrow with the next as quickly and accurately as possible. This environment stimulates CoG control while the subject is “walking” distances within the VE. Thus, CoG controlled displacement is made dynamically contingent on purposeful movement and vice-versa, as it is in real walking. This is expected to make an individual more confident on his/her ability to control shifts of the CoG and to be better able to generalize the benefit to real conditions.

The second program features an indoor path with rooms of variable dimension, obstacles to negotiate and corridors of variable lenghth. Some of the environments are painted with high contrast vertical stripes or have squared patterns on the floors to induce a “natural” optokinetic stimulation during movement. In order to navigate this VE the trainee needs to exert a more accurate control over CoG and learn to ignore the interference of optokinetic stimulation. The data of two healthy subjects F. (female 27 yrs) and D. (male, 40 yrs) performing on the outdoor virtual track are reported in Table 1.

Table 1. *Velocities and displacements of each marker in two healthy controls performing on the outdoor VR path*

F., female, 27 yrs.

Marker	Mean velocity (cm/sec)	lateral velocity (cm/sec)	longitudinal velocity (cm/sec)	longitudinal path (m)	lateral path (m)	total distance (m)	global displacement (m)
Front	19.36	15.00	7.82	0.86	1.65	2.13	0.09
Rear	2.75	1.66	1.25	1.06	1.41	2.34	0.06
Left	3.59	1.73	2.13	1.51	1.23	2.55	0.08
Right	4.91	2.81	2.79	1.20	1.21	2.11	0.05

D., male, 40 yrs.

Front	14.00	11.00	5.73	1.72	3.30	4.20	0.02
Rear	8.40	5.24	4.61	2.86	3.25	5.21	0.08
Left	5.07	2.78	2.85	3.51	3.42	6.24	0.06
Right	4.62	2.67	2.50	3.25	3.47	6.00	0.07

Table 2. *Velocities and displacements of each marker in an MS patient before and after vestibular rehabilitation*

FIRST TRIAL

Marker	Mean velocity (cm/sec)	lateral velocity (cm/sec)	longitudinal velocity (cm/sec)	longitudinal path (m)	lateral path (m)	Total distance (m)	global displacement (m)
Front	8.75	6.03	3.94	11.47	17.54	25.45	0.12
Rear	7.84	4.69	4.32	4.67	5.07	8.47	0.14
Left	6.59	4.05	3.36	10.74	12.96	21.09	0.13
Right	6.89	3.90	3.91	12.09	12.04	21.29	0.14

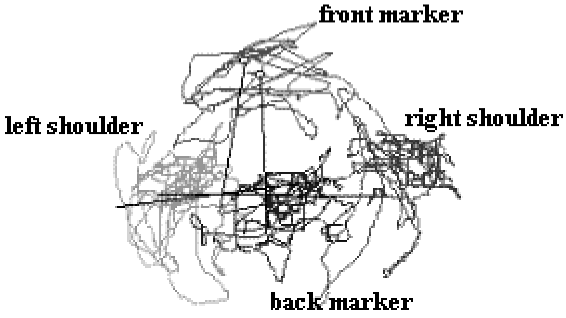
II TRIAL

Front	12.22	9.11	5.30	4.35	7.47	10.02	0.11
Rear	4.76	2.69	2.52	3.71	3.95	7.00	0.07
Left	8.63	3.85	6.09	5.54	3.50	7.85	0.11
Right	5.76	2.84	3.63	4.43	3.47	7.03	0.17

In both subjects the front marker moves faster as if the movement of the head was performed with a posterior fulcrum while the velocities of the right and left shoulders were comparable. The velocities in both the longitudinal and lateral directions are also similar: the subjects remained on the spot (low global displacement values) while bending in both directions. However, D. travelled a longer distance in the VE than F.; i.e. he had more difficulties in the control of his shifts of CoG.

In Table 2 the data of a patient with multiple sclerosis (M., female 51 yrs. old) who was trained with the same VR program are reported. Figure 2 compares the raw traces of a healthy subject with those of the patient during her VR retraining sessions. The first trial was recorded at the beginning of treatment, the second after a period of two weeks of rehabilitation, including physical and traditional instrumental techniques. In the first trial velocities were generally lower than those of healthy subjects (compare to Table 1). The movements of the head and the trunk were similar: i.e. the patient was not able to dissociate the head from the trunk, and she moved her head more laterally than longitudinally. The global displacement was also higher than in controls (she could not avoid stepping away on the platform) and the distance travelled in the VE (total distance) was higher than expected.

In the second trial, the velocities of the shoulder markers were not modified, but the movements of the head and trunk became more independent, as shown by an increase of front velocities values and a contemporary decrease of the back values. Furthermore, the total distance travelled in the VE was smaller than in the first trial. We suggest that vestibular rehabilitation allowed the MS patient to optimize her head/trunk and ankle\hip strategies to control her travel along the same virtual path.



Healthy control (40 yrs.)

MS patient (51 yrs.), 1st trial

MS patient (51 yrs.), 2nd trial

Figure 2. *Trajectories of the 4 markers during vestibular VR training sessions with the program simulating an outdoor path.*

4. CONCLUSIVE REMARKS

Consistent with the definition of equilibrium as a psycho-motor performance in which the vestibular system provides a continuous integration of multisensorial cues, modern assessment of vestibular dysfunction and vestibular rehabilitation should benefit from methodologies based on psycho-motor multisensorial stimulation.

The human equilibrium system derives much of its strength and plasticity from the influence of permanent stimulation from the world we live in. Failures of the sensory inputs as well as of the central equiliubrium regulation may lead to vertigo, nausea and vomiting, blurred vision, nystagmus, head and body instability, changes in cardiac rythm, and metabolic alterations. The system has many inborn possibilities for internal stabilisation and compensation (Smith and Darlington, 1991). This term describes a type of central nervous counterregulation which occurs as a result of functional damage. It utilises supplementary functions which "mask" the underlying dysfunction which, however, continues to exist, and can, in special conditions, manifest itself. Specifically, vestibular compensation means the disappearance of all asymmetries (static and dynamic) in the ocular and spinal vestibular responses along with a more central plastic reorganization of the reflexes. This process may be defined as an error-controlled goal-directed learning. The goal of vestibular rehabilitation is to train the patient to learn substitutive and compensatory behavioural strategies. The main problem of current visual-feedback procedures is the poor transfer of motor skills learned during rehabilitative sessions into daily life activities.

VR is a technology that is already known to be capable of involving patients in a wide range of learning experiences (Rizzo et al., 1997). Also in the case of vestibular rehabilitation, VR may provide the right "dynamic cognitive and spatial milieu" to link CoG control to activities of daily living such as exploration and navigation of continuously varying environments. This would stimulate in a very complex way the compensatory mechanisms and would prevent the establishment of too specific associations between the control of equilibrium and the environmental conditions in which that control is achieved. The use of a reliable methodology to quantify learning of CoG control is suggested to be as important as the combination of the appropriate virtual environments with the appropriate cognitive tasks to optimize the outcome of the retraining.

Studies are only at the beginning, however. More systematic investigations need to be carried out in at least two main directions: to understand more concerning the interplay between vestibular function and cognitive activities related to orientation and the exploration of the surrounding space, and to assess the efficacy and the generalization of VR-based vestibular rehabilitation.

5. REFERENCES

D Alpini, L Pugnetti, A Cesarani, L Mendozzi and E Barbieri (1996), Evaluation of vestibular strategies in human exploration of the environment by means of immersive virtual reality, In *Giddiness and Vestibulo-Spinal Investigations* (CF Claussen, MV Kirtane, L Constantinescu & D Schneider, Eds), Elsevier Science, Amsterdam, pp. 315-323

RA Andersen, LH Snyder, CS Li and B Stricanne (1993), Coordinate transformations in the rapresentation of spatial information, *Curr. Opin. Neurobiol.*, **3**, pp. 171-176.

R Kohen-Ratz (1977), *Psychobiological aspects of cognitive growth*. New York: Academic Press.

BL Mc Naughton (1987), Neural association of movement and space: preliminary steps toward a non-cartographic theory of spatial rapresentation and learning, *Neurosci. Lett.* ,**Suppl. 29**, pp. 143-144.

L Pugnetti, L Mendozzi, EA Attree, E Barbieri, BA Brooks, CL Cazzullo, A Motta and DF Rose (1998), Probing memory and executive functions with virtual reality: past and present studies, *Cyberpsychol. Behav.,* **1**, 2, pp. 151-161.

A Rizzo, JG Buckwalter and U Neumann (1997), Virtual reality and cognitive rehabilitation: a brief review of the future, *J. Head Trauma Rehab.,* **12,** pp. 1-15.

PF Smith and CL Darlington, (1991), Neurochemical mechanisms of recovery from peripheral vestibular lesions (vestibular compensation), *Brain Res. Rev.*, **16**, pp. 117-133.

K Stanney , G Salvendy, J Deisinger et al., (1998) Aftereffects and sense of presence in virtual environments: development of a research and development agenda, *Int. J. Human-Comp. Interact.,* **10**, 2, pp. 135-187

S Wapner and HA Witkin (1950), The role of visual factors in the maintenance of body balance, *Am. J. Psychol.*, **66**, pp. 385-408